UNIVERSITY OF STRATHCLYDE

DEPARTMENT NAVAL ARCHITECTURE, OCEAN, AND MARINE ENGINEERING

Design and Enhancement of Ship Recycling Facilities by Considering Risks and Productivity in an Integrated Framework

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ABSTRACT

This thesis explores the design and enhancement of ship recycling facilities, focusing on the integration of risk management and productivity improvement. The study aims to address the complex challenges faced by the ship recycling industry, particularly in developing countries like Indonesia, where environmental sustainability and worker safety are often compromised.

The research begins with a thorough investigation of the hazards associated with ship recycling activities. Extensive field studies, workshops with industry experts, and best practice guidelines were employed to identify and categorize these hazards. This foundational work provided the basis for a comprehensive analysis of health, safety, and environmental (HSE) risks, incorporating detailed data collection and empirical case studies.

A key contribution of this thesis is the development of a robust risk assessment framework tailored specifically for ship recycling yards. This framework integrates established risk assessment methodologies and probability calculations, offering a structured approach to identifying, evaluating, and mitigating risks. Additionally, the thesis introduces the use of Discrete Event Simulation (DES) to optimise productivity and cost in ship recycling operations. By utilising ARENA software, the research provides a detailed cost-benefit analysis of various risk control measures, highlighting opportunities for efficiency improvements.

The proposed framework was validated through empirical case studies conducted in Indonesian ship recycling yards. These studies underscored the practical challenges and risks inherent in the ship recycling process, demonstrating the framework's applicability and effectiveness in real-world settings. Furthermore, the research explores the potential for growth and development in the Indonesian ship recycling industry, identifying strategic locations and evaluating economic and regulatory factors.

In general, this thesis contributes to the field by presenting an integrated approach to improving safety, environmental sustainability, and economic efficiency in ship recycling. The findings offer valuable insights for policymakers, industry stakeholders, and researchers, paving the way for safer and more sustainable ship recycling practices globally.

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Chapter 1. Introduction

1.1 Chapter Overview

This chapter specifies an introduction into the research topic being investigate in this PhD study and explains the foundations of this study provides justification to focus this PhD research into ship recycling.

1.2 General Perspective

Shipping is an essential transportation mode, contributing to between 80% and 90% of global trade, transporting approximately 10 billion tonnes of container, solid and liquid bulk freight across the world's oceans (Walker et al., 2019). However, it may become economically not efficient to operate ships, when they get older. It is estimated that the average age of demolished vessels is around 30 years Rahman, Handler, & Mayer, 2016). Therefore, when the costs associated with operating such vessels exceed the potential gains, the shipowners tend to stop operating these vessels. They either sell it to other ship owner or consider sending their vessel to recycling yard, while ship recycling is one of the options for a ship that has reached the end of its operational lifespan.

Ship recycling is a process which involves dismantling obsolete and inoperable vessels, and allowing for the reuse of valuable materials (Ozturkoglu et al., 2019). As a result, 95 to 98% of the ship's material and equipment in terms of weight can be recycled, which made recycling process is a vital part of a ship's life span since it ensures that all-important materials are collected, reconditioned, remanufacture, or recycled when its operation/useful life is over.

According to the Environmental Protection Agency, ship recycling, just like every other recycling sector, can be regarded as the most environmentally friendly option for end-of-life vessels in comparison to other alternatives such as sinking and abandoning the vessel (Du et al., 2018; Favi et al., 2018; Gunbeyaz et al., 2019). Extensive research has been done on the materials, equipment, and machinery which may be recovered from decommissioned ships. These materials, equipment, and machinery have the potential to be reused, reconditioned remanufactured and recycled. Ship recycling sector is particularly significant for developing nations such as Indonesia since these materials can be repurposed in various sectors. For example, metal from a ship may be rerolled/melted and reused in the construction, which is highly beneficial. Aside from that, additional shipboard equipment can be used aboard ships (while they are being refitted or repaired) or in other sectors.

In general, ship recycling practice has been done in developing countries such as India, Bangladesh, Pakistan, and Indonesia. However, developing countries are failing to recycle these e old vessel in safe and sustainable manner, since ship recycling is one of the world's most hazardous jobs as this sector is associated with the high occurrence of accidents and occupational diseases (Graham-Rowe, 2004). Ship recycling entails various tasks and procedures that may expose workers to dangerous working conditions leading to mishaps, accidents, health issues, injuries, and even death (OSHA). This Figure 1.1 below shows the number of accidents in the past seven years in South Asia. According to the figure, in total, 117 accidents were documented, between 2014-2021. However, it needs to be noted that only small number of accidents are reported in this sector. Those accidents that are reported lacking significant details because they are generally reported by 3rs party such as NGO's. This situation makes safety learning nearly impossible.

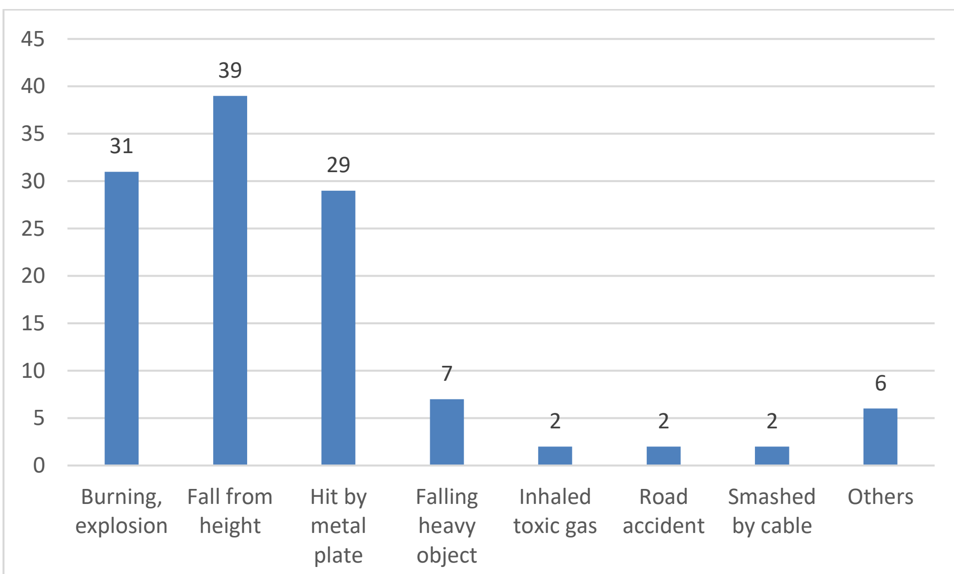


Figure 1. 1: Number of accidents in South Asia ship recycling yard in 2014-2021 (NGO Shipbreakingplatform)

Furthermore, the consequence of accident can be categorize as shown in Figure 1.2 below. It can be seen that Fire related accident (burning, explosion), falling from height, hit by objects are the most common accidents in ship recycling yards.

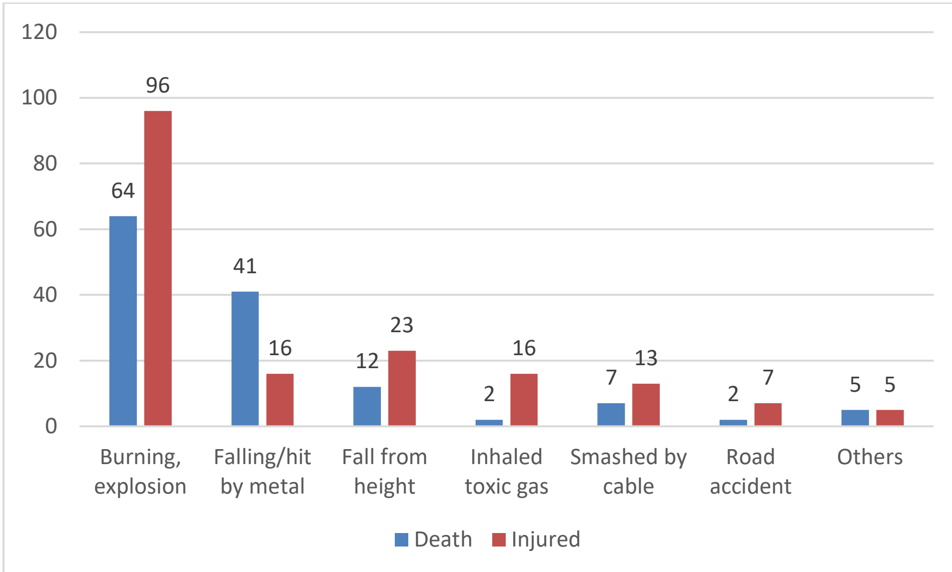


Figure 1. 2: The consequence for accident in South Asia ship recycling yard in 2014-2021 (NGO shipbreakingplatform)

In addition to common occupational accidents, old ships contain significant amounts of dangerous substances, such as heavy metals, petroleum-based hydrocarbons, and other xenobiotic substances (Patel et al., 2015; Patel et al., 2013; Reddy et al., 2005) When improperly handled, these pollutants accumulate in coastal sediments, posing considerable health and environmental risks.

To mitigate these issues, regulatory frameworks such as the Basel Convention on the Transboundary Movements and Disposal of Hazardous Wastes, the IMO Hong Kong International Convention (HKC) for the Safe and Environmentally Sound Recycling of Ships, and the European Union's Ship Recycling Regulation (EUSRR) have been established. The Basel Convention, in effect since 1992, laid the groundwork for hazardous waste management, while the HKC, adopted in 2009, specifically targets safe and sustainable ship recycling practices. The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships entered into force on 26 June 2025. From this date, all ships destined for recycling must carry an Inventory of Hazardous Materials (IHM) covering Parts I–III and obtain an International Ready for Recycling Certificate (IRRC). Recycling facilities must also be authorised and maintain a Ship Recycling Facility Plan that addresses worker safety, emergency preparedness, and environmental controls. These regulatory developments reinforce the global push for safe, sustainable recycling and provide the compliance context for this research (IMO, 2025a; IMO, 2025b; Bureau Veritas, 2025; Lloyd's Register, 2025; DNV, 2025).

Meanwhile, In recent years, digital twin technology has begun to revolutionise maritime safety and risk management. Digital twins integrate real-time data with advanced modelling to predict failures, assess risks dynamically, and optimise operations (Zio and Miqueles, 2024; VanDerHorn et al., 2022). While this study focuses on discrete-event simulation, acknowledging digital twins provides important context. The chosen approach was selected because it is well suited to modelling process bottlenecks, queueing, and resource constraints in ship recycling, while remaining compatible with future digital twin platforms as live operational data become available.

Despite these regulations, the ship recycling industry in developing countries faces increasing operational costs as it works to comply with global environmental and safety standards. Facilities adhering to high health, safety, and environmental (HSE) standards often face competitive disadvantages, as competitors who cut costs by neglecting these standards can offer ship owners more favourable prices. This dynamic intensifies a "race to the bottom" in HSE compliance, leaving facilities that pursue "green" recycling with higher operational expenses.

A critical challenge in this industry lies in Optimising processes to maintain environmental and worker safety without compromising cost-efficiency. Addressing this issue requires a deeper understanding of the operational constraints and hazards faced by ship recycling facilities in developing countries. However, limited data restricts effective modelling of current practices and hinders accurate risk assessments, underscoring the importance of a systematic investigation. Such an inquiry would provide essential insights into the risks and productivity limitations of existing ship recycling practices, guiding the development of safer, more efficient processes that align with global regulations.

Furthermore, this need for enhanced insight shapes whole research focus of this thesis. Contemporary ship recycling discourse increasingly focuses on sustainability, social justice, and circular economy outcomes. Beyond compliance, circular economy principles encourage designing systems that enable safe disassembly and reuse of materials at their highest value (ElMenshawy et al., 2024; Tola et al., 2023). Issues such as worker rights, community health, and equitable value distribution are central to current debates. This study does not attempt to solve all these challenges but instead focuses on integrating risk with productivity and cost at the facility level. This narrower focus contributes to sustainability by reducing unsafe practices and inefficiencies, while acknowledging that broader circularity and social justice aspects require additional frameworks and policies beyond the scope of this research. By systematically investigating the risks and limitations associated with current ship recycling practices, this study aims to build an evidence-based framework that will support safer, more efficient recycling processes. This framework, ultimately, will facilitate the implementation of industry guidelines that address both productivity and regulatory compliance, as will be discussed in subsequent chapters.

1.3 Overview of the Approach

The thesis adopts a structured approach to address productivity and risk management in ship recycling. The primary objective is to develop a framework that combines risk mitigation with productivity improvement, given the lack of such an integrated approach in existing ship recycling frameworks. Key steps include:

- **Investigation and Assessment**: This phase involves reviewing literature on safety, productivity, and related industries such as shipbuilding to understand existing methods. It also includes identifying the need for discrete-event simulation and risk assessment specifically within the context of ship recycling. Before starting the development of the framework, it was essential to conduct a comprehensive investigation of the literature on the ship recycling industry. The findings of this investigation outcomes will be summarised in Chapter 2. Prior research has linked risk assessment to operational planning in ship recycling. While some studies, such as Hiremath et al. (2016), have addressed risk assessment and planning for ship recycling, there remains no integrated study that combines risk, cost-benefit analysis, and productivity modelling. This research addresses that gap by linking risk control measures with discrete-event simulation and economic evaluationThis thesis addresses this gap by coupling quantified risk with process simulation and cost-benefit evaluation. Therefore, the research conducted in similar industries (shipbuilding industry and other dismantling/recycling industries) needs to be investigated to comprehend the approach and implement it to ship recycling with all the essential factors. In order to develop an integrated approach, previous research on risk assessment will be studied in detail to identify a suitable approach to link to the ship recycling process. A simulation study for the development and optimisation of a ship recycling developed by Gunbeyaz (2019) will be integrated in the risk assessment framework to calculate productivity.

- **Framework Development**:
  The developed framework is then applied to investigate ship recycling risks through a structured approach consisting of the following components
    - *Ship Recycling Risk Investigation*: Detailed studies in ship recycling yards, expert consultations, and data gathering for precise simulations.
    - *Hazard Identification*: Compiling a list of hazards tailored for ship recycling, guided by expert analysis.
    - *Risk Analysis*: Using modelling tools to assess accident scenarios, focusing on high-risk areas.
    - *Risk Control Options (RCOs)*: Identifying and evaluating measures to control risks, forming logical regulatory choices.
    - *Productivity Measurement*: Using discrete-event simulation to assess the impact of RCOs on efficiency.
    - *Cost-Benefit Analysis*: Evaluating RCOs for cost-effectiveness, including indices like Gross and Net Cost of Averting Fatalities.

- **Implementation and Analysis**: The developed framework is applied through case studies that utilise real-world shipyard data collected from field studies, interviews, and workshops. The chapter concludes with a summary of the methodological framework, emphasising its data-driven foundation, tailored hazard identification, risk control measures, and cost-benefit evaluation, aiming to create a practical and traceable approach for risk-based productivity improvements in ship recycling. Following the development of the risk assessment and simulation models framework, the capabilities of the developed approach will be demonstrated through a case study in Indonesia. The risk framework requires a systematic and transparent step involved in conducting risk assessment, data, and application. Several well-known probability calculation techniques are also explained and compared. The simulation approach requires comprehensive data on the operation, process times, and costs to succeed. Therefore, a data collection campaign will gather the missing data. A field study will collect operational data from an actual ship recycling yard(s). The data collection study in the yard will be combined with interviews with recycling experts, other stakeholders, and equipment manufacturers where necessary. Moreover, ShipDISMANTL and DIVEST projects and the previous study (Gunbeyaz, 2019) also collected partial data on the operation, and the appropriate data will be utilised within the case study.

1.4 Structure of the Thesis

Furthermore, this PhD thesis flows as follows:

- Chapter 2 presents the findings of literature review in ship recycling research field, as a part of this, a review of risk studies in ship recycling and similar industries has been conducted. Furthermore, a review of optimisation studies was also conducted. It describes the ship recycling problem in general and challenges in improving the yard in relation to the current and upcoming regulations. It also highlights the limitations of the existing risk assessment methodology in ship recycling that failed to address the additional benefit of improvement in terms of productivity. It was identified that a structured approach for productivity assessment and cost-benefit analysis are missing.
    - Chapter 3 defines the research question, aim, and objectives of this study.
    - Chapter 4 briefly describes the approach adopted to achieve the aims and objectives.
    - Chapter 5 provides an in-depth examination and comparison of the risk-based approach and the safety analysis methodologies First, a risk-based approach that has been applied in many areas is introduced. Starting with explaining risk-based approaches, the chapter follows a comparative analysis for each approach in line with the ship recycling case. Furthermore, safety analysis methods applied to the risk-based design are explained as well as the limitations of applying the generic framework to ship recycling are discussed.
    - Chapter 6 explores the application of modelling and simulation techniques in the context of improving HSE compliance and productivity efficiency in the ship recycling process.

- Chapter 7 describes the development of Risk-Based Ship Recycling Yard Improvement Framework
- Chapter 8 explains the integration of Discrete Event Simulation (DES) with Cost-Benefit Analysis (CBA) in ship recycling operations.
- Chapter 9 focuses on the of Indonesian context and describe the potential of ship recycling development by identifying the criteria for location selection, investigating the suitable locations for ship recycling yard development, and selecting appropriate locations for the Indonesian ship recycling industry through field studies, workshops, and targeted surveys to local and international experts.
- Chapter 10 presents the case study 1.
- Chapter 11 presents the case study 2.
- Finally, Chapter 12 and 13, discusses and concludes the thesis and highlights potential future avenues of this research.

1.5 Chapter Summary

This chapter has provided an overview of the ship recycling industry, highlighting its inherent challenges and discussing the problems faced by stakeholders in the sector. The background information presented gave an understanding of the complexity of the industry, which is required to ensure environmental sustainability, worker safety, while ensuring economic profitability, is at levels which allow company to survive the competition to stay in business.

Chapter 2. Literature Review

2.1 Chapter Overview

This chapter provides a comprehensive review of the current state of global ship recycling, focusing on key aspects such as operational practices, regulatory frameworks, health and safety risks, productivity, and sustainability. It begins by outlining global market trends, ship recycling methods, and business challenges, followed by an overview of current and upcoming regulations, including the Hong Kong International Convention (HKC) and the EU Ship Recycling Regulation (EU-SRR). The second part of the chapter reviews recent literature to identify gaps, with a particular focus on the integration of risk assessment and productivity improvement in ship recycling practices. This review forms the foundation for the research framework developed in later chapters.

To ensure that the literature review is comprehensive and up to date, a structured search process was adopted. Searches were carried out using academic databases including Scopus, Web of Science, and Google Scholar, ensuring broad coverage across engineering, environmental science, and maritime management literature. In addition to peer-reviewed sources, grey literature was also considered, such as International Maritime Organization (IMO) publications, NGO Shipbreaking Platform reports, EU regulatory documents, and guidance issued by classification societies (e.g., Lloyd's Register, DNV, Bureau Veritas). This combination ensured a balance between academic research and practical industry perspectives. The search covered publications from 2015 to 2025, capturing recent developments such as the 2025 entry into force of the Hong Kong Convention and advances in circular economy approaches to ship recycling. The main search terms included: *"ship recycling," "ship breaking," "risk assessment," "health and safety," "cost-benefit analysis," "productivity," "simulation," and "circular economy."*

While the main search focused on publications from 2015 to 2025, a small number of earlier studies were included where they represent foundational theories or significant historical developments in ship recycling practices.

Inclusion criteria:

1. Studies that addressed ship recycling practices, health and safety risks, regulatory frameworks, productivity improvements, or sustainability and circular economy issues.

2. Empirical research, case studies, reviews, and authoritative grey literature with practical relevance to ship recycling.
3. Both English and non-English publications, with non-English sources reviewed using translation tools or expert interpretation where required.

Exclusion criteria:

1. Studies unrelated to ship recycling or end-of-life (EoL) ship management.
2. Purely theoretical studies with no operational or regulatory relevance.
3. Duplicate publications across databases.

The selected literature was grouped into four main thematic areas:

1. Ship recycling processes and methods,
2. Economic and market factors,
3. Regulatory frameworks and governance, and
4. Sustainability and enabling technologies, including circular economy strategies and digitalisation.

Through following this structured approach, the review ensures inclusion of diverse and international perspectives, creating a robust and representative foundation for understanding the global ship recycling landscape. This provides the necessary background for identifying research gaps and developing the integrated framework presented in later chapters.

2.2 Ship Recycling Industry Overview

Upon termination of their operational life, ships are conveyed to specialised facilities for recycling. Ship recycling, also known as ship breaking, involves the complete or partial dismantling of a ship to recover components and materials for reprocessing, reuse, or disposal (IMO-HKC, 2009). On average, ships have a service life of around 30 years (Rahman, Handler, & Mayer, 2016). The recycling process encompasses various stages, from mooring or beaching to material recovery and repurposing.

Compared to other end-of-life options like reefing or abandonment, ship recycling stands out as the more environmentally friendly alternative, similar to other recycling industries (Du et al., 2018; Favi et al., 2018; Gunbeyaz et al., 2019). Decommissioned ships are treasure troves of materials and equipment, many of which have potential for reuse, repair, and recycling. Countries like Indonesia greatly benefit from the ship recycling industry. Extracted metals can be repurposed in sectors such as construction, while salvaged equipment finds uses in refurbished ships or industries requiring diesel generators, boosting the local economy.

However, these ships can also harbour hazardous waste, and the practices in many developing nations often risk human and environmental safety. Such practices have drawn criticism from global stakeholders, prompting the need for more stringent regulations like the International Maritime Organisation's (IMO) Hong Kong Convention.

Historically, ship recycling existed as a concept but became a prominent industry after World War II, especially after the need to dismantle numerous wartime ships (McKenna, 2013). While initially cantered in developed nations, stricter health, safety, and environmental regulations coupled with changing steel demands caused a shift to developing Asian countries. Presently, the majority of ship recycling occurs in Bangladesh, India, China, Pakistan, and Turkey, which collectively handle almost 99% of the world's ship recycling (NGO Ship Breaking Platform, 2017). However, the often lenient or poorly enforced health, safety, and environmental (HSE) regulations in these nations have been widely criticised for exposing workers and surrounding communities to hazardous conditions (Ahamad et al., 2021). International norms and standards, such as the IMO's Hong Kong Convention and the European Union's Ship Recycling Regulation, have been introduced to address these challenges (European Commission, 2016).

2.2.1 Current Market and Locations

The Figure 2.1 below illustrates the number of ships recycled from 2000 to 2020 in various countries, compiled from NGO Ship Breaking Platform (2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017)Shipbuilders' Association of Japan (2016) Overall introduction to the current market. Bangladesh currently leads the ship recycling industry (in terms of gross tones dismantled), followed by India, China, Pakistan, and Turkey in terms of the steel volume dismantled.

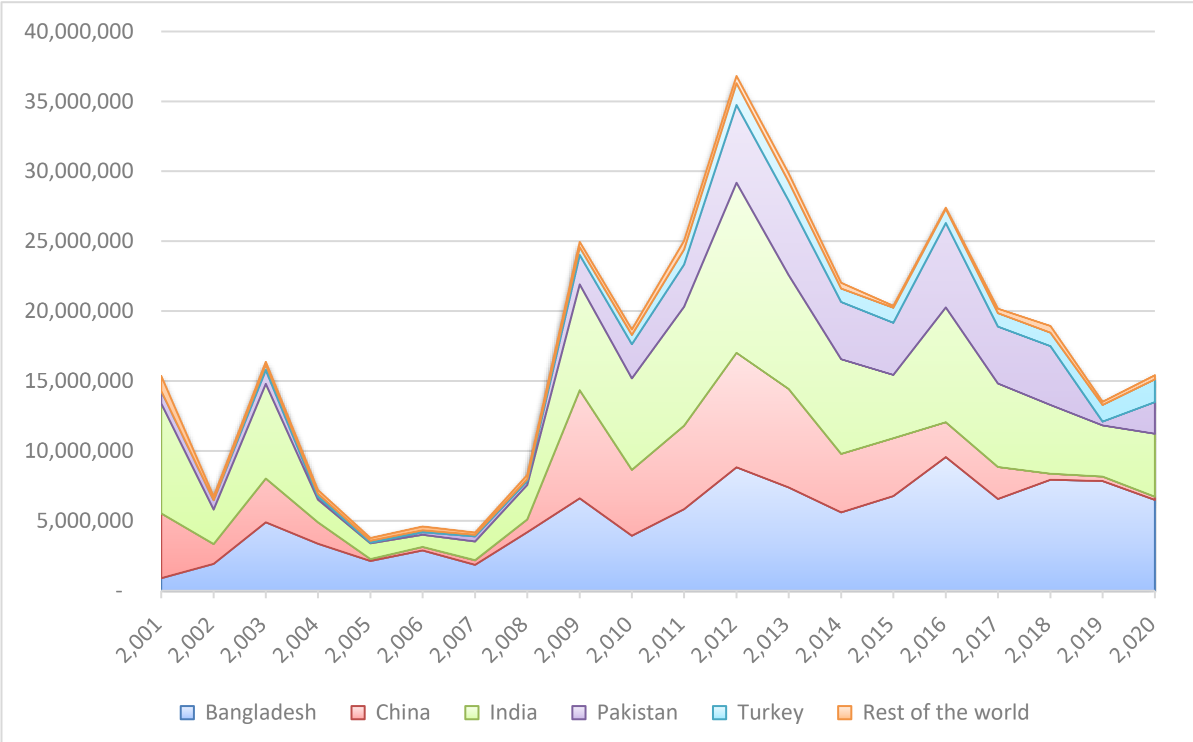


Figure 2. 1: Ship recycling capacity according to countries (in '000 gross tonnes), compiled from NGO Ship Breaking Platform (2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017), Shipbuilders' Association of Japan (2016)

2.2.1.1 Bangladesh

Bangladesh's economy is heavily dependent on the ship decommissioning and recycling industry, which plays a vital role in supplying scrap steel to the domestic iron and steel sectors. Since the country has no local metal ore mining industry, the ship-breaking sector fulfills a significant portion of its steel demand, particularly through re-rolling mills that process recycled materials (Sitakunda Upazila, 2025). This industry has evolved into a strategic economic engine, providing direct employment to over 200,000 people and many more indirect jobs, with workers often coming from economically disadvantaged and marginalised communities (Chittagong Ship Breaking Yard, 2025; Ship Breaking, 2025). Most shipbreaking yards in Bangladesh are located on the government-owned property and are operated under leasehold agreements. However, there are several ship-breaking yards which have also been developed on privately held property in the area (Rizvi, 2020). Most Bangladeshi ship recycling industry is located along the Sitakunda coast, 12 km from Chittagong (Sujauddin, 2015). Bangladesh ship recycling yard are employing very simple and inexpensive, process to deconstruct the ship, as seen in the illustration below.

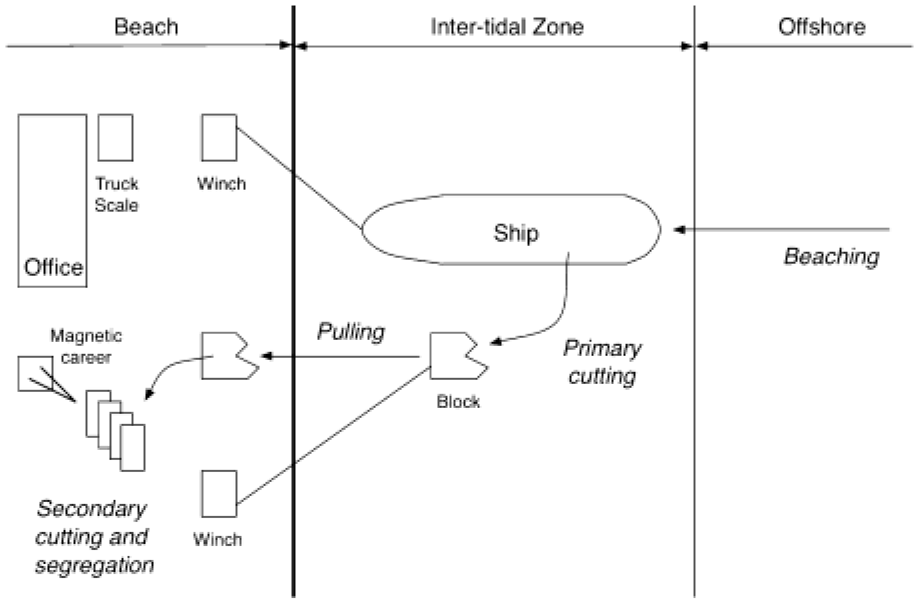


Figure 2. 2: Beaching method in ship breaking yard Bangladesh (Sujauddin, 2015)

Supported by its geographical conditions, since 2015, Bangladesh has became the global market leader due to volume of ship dismantled. The data in 2020 shows that Bangladesh dismantled 42% of the ships, India dismantled 29%, and Pakistan dismantled 15% (NGO shipbreaking platform, 2020).

Despite its existence for supporting their economics and needs of steel, Bangladesh shipbreaking and recycling industry is criticized for putting the workers in hazardous working conditions, causing environmental pollution, and using child labour in the yards (Hossain, 2015). In response to the ruling of the High Court Division of the Supreme Court, the Ship Breaking and Recycling Regulation 2011 was established with the aim of ensuring safe and environmentally sound ship recycling practices in Bangladesh. As part of its compliance with the IMO Hong Kong Convention, Bangladesh has enacted new legislation, dubbed the Bangladesh Ship Recycling Act, 2018 (BSRA) (Tanha, 2022). Although the government and international bodies such as IMO and NORAD support the transitional process (Gunbeyaz, 2019), human and environmental risk problems still exist. Bangladesh's solid waste management system is not performing at an adequate level. Even though local governments, non-governmental organisations, and the informal sector have committed enormous resources, they cannot effectively control and handle them (Alam, 2020). It is important to note that the shipbreaking or ship recycling sector in Bangladesh is still considered as a high-risk profession, with a documented history of multiple fatalities (Tanha, 2022). It is estimated that 10–15 employees are lost their lives, and 150 workers are badly injured on an annual basis in this business, according to Sujauddin, 2015. Regarding the most recent report from an NGO ship-breaking platform, at least ten employees died, and another fourteen were badly injured in Bangladesh in 2020 (NGO, 2020).

2.2.1.2 India

According to NGO Ship Breaking Platform's Annual Report, India was the leader in the volume dismantled until 2014 but currently ranked second amongst the ship recycling in 2019 and 2020 (NGO Ship Breaking Platform, 2019, 2020). Around 4,5 million GT ships were recycled in India in 2020, which means 29% of the total recycled ship worldwide (NGO Ship Breaking Platform, 2020). Indian ship recycling is taking place along the coast of Alang - Gujarat. Alang beach in the Gulf of Cambay, 56 kilometers away from Bhavnagar district, is a major ship recycling site in India (Demaria, 2010; Deshpande 2012). According to Figure 2.3, there are a total of 171 ship recycling yards, with 92 located in Alang and 79 in Sosiya over a 12 km area (Deshpande, 2012).

Figure 2. 3: Map Depicting the Distribution of ship recycling plots in the Alang-Sosiya region (Wikipedia, 2022)

India's ship recycling yards have improved following the Hong Kong Convention. Nevertheless, beaching is still not recognized by current conventions and is causing environmental damage to ship recycling areas (Gunbeyaz, 2019). There are 100-125 m long workspaces between Alang's high-tide line and departure gates, and most yards are 60 m wide. The ship is positioned in the inter-tidal zone, as depicted in Figure 2.4, which is the area located between the high and low tide lines.

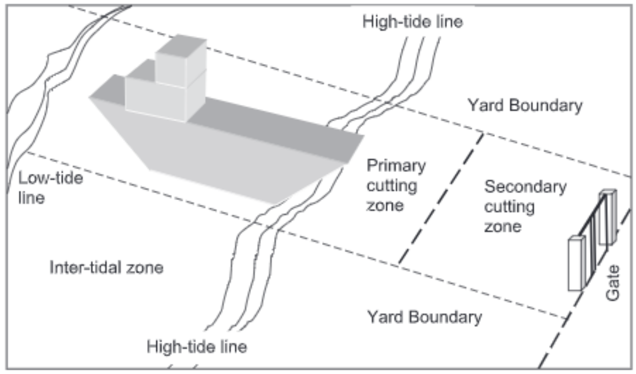


Figure 2. 4: A schematic representation of a typical ship recycling yard, including the notional yard boundaries, gate, and the ship beached between the high-tide and low-tide lines. (Hiremath, 2016)

As per a report submitted by the Technical Experts Committee, which was established to assess the labour conditions in Alang, India, the fatality rate in the shipbreaking industry was found to be 2 fatalities per 1000 workers. This is in comparison to the fatality rate in the mining industry, considered as the most accident-prone, which was recorded at 0.34 fatalities per 1000 workers across India during the same period (Sahu 2014). In 2018, a minimum of 14 workers lost their lives at Alang, resulting in one of the highest fatality rates in recent years in Indian ship recycling yards (NGO shipbreaking platform).

Several ship recycling yards in India assert that they have modernized their beaching operations to align with the requirements outlined in the Hong Kong Convention, as established by the International Maritime Organisation. Recent European Commission inspection visits to Alang, as well as media reports, have raised serious concerns about intertidal pollution, a lack of medical facilities, violations of labour rights, and a lack of competence to securely handle several hazardous waste streams, including mercury and radioactively contaminated materials that are commonly found on offshore oil and gas units. There are no South Asian facilities that fulfil the EU's safety and environmental standards. (2019, NGO shipbreaking)

2.2.1.3 Pakistan

The ship dismantling sector in Pakistan is situated in the vicinity of Gaddani, which features a 10-mile long shoreline (depicted in Figure 2.5). Approximations suggest that there are approximately

15,000 individuals who are directly employed in the 68 active ship recycling yards (NGO Ship Breaking Platform, 2013b).

Figure 2. 5: Gadani region shore, ship recycling yards along the coastline (Google Maps, 2015)

The number of accidents and casualties is not very clear on the occupational health and safety side, as there is no reliable record keeping. Even though the accidents are not reported well, they are familiar and similar to India and Bangladesh (Gunbeyaz, 2019)

This study of the Gadani shipbreaking yards in Pakistan explores the concepts of the Basel Convention and the Hong Kong Convention as they pertain to environmentally and socially responsible ship recycling practices. The NGO Shipbreaking Platform has analysed the global economic and legal context in which the shipbreaking industry operates in Pakistan and has evaluated the technological, infrastructural, and procedural mechanisms that are in place in the Gadani yards to protect human health and the environment. According to Hiremath (2015), the Gadani ship dismantling yards have implemented crucial technologies, infrastructures, and procedures to secure human health and well-being. Most of the time, the dangerous compounds included in the vessel's structure are not even correctly identified, resulting in personnel being exposed to them without their knowledge. Large quantities of hazardous chemicals are then illegally discarded or resold in regional marketplaces, resulting in a vicious cycle. Bangladesh and Pakistan do not have a garbage treatment, storage, or disposal site (NGO shipbreaking). The situation in Pakistan's shipbreaking yards is not any better than elsewhere.

In India and Bangladesh, the yards at Gadani operated directly on the beach, with no intermediate structures and drained working areas to protect the sea and sand from pollution. In the Gadani shipbreaking area, hazardous substances, including asbestos, polychlorinated biphenyls (PCBs), and residual oils, are being disposed of indiscriminately without any established mechanism for the management of hazardous waste. The health and safety of Gadani's employees are entirely disregarded. Following the explosion of the ACES tanker on November 1, 2016, there has been a greater awareness, both domestically and globally, of the hazards that employees at shipbreaking yards in Pakistan are exposed to. The explosion claimed the lives of many employees, and it required the Pakistani military three days to put it out.

2.2.1.4 China

NGO Shipbreaking platform found that there are three ship recycling yards in China, each located in a different region of the nation. The two most crucial ship recycling clusters are located along the Pearl River at Xinhua and in the surrounding area of Shanghai, respectively (along the Yangtze River and on Zhoushan Island). In addition, a ship recycling factory is located in Dalian, located in northern China. Due in part to low steel costs, several Chinese yards with the capacity to recycle a significant number of big vessels across piers and at docks have gone out of business in recent years. The Chinese government had a financing program to encourage local scrapping and construction of boats owned and flagged by Chinese companies; however, the program was recently terminated. China has also blocked the market for recycling foreign-flagged ships as of the first day of January 2019. These measures to combat pollution and trash production in China are being backed up by a prohibition on importing a significant number of hazardous wastes, especially plastics, which came into effect earlier this year.

Since China ended the recycling of foreign vessels on its coastlines in late 2018, there has been a mounting call from the maritime sector for the resumption of the activity. Concerns have been raised that many shipbreakers in other parts of Asia do not follow the current environmental and safety regulations. As a result, China may be considering reversing its ban on foreign ships being recycled on its ports. China enacted the restriction at the end of 2018, but the government appeared to be on the verge of overturning it so that ship owners would have more environmentally friendly ship recycling options than they would have had in other South Asian yards.

2.2.1.5 Turkiye

Since 1976, the process of ship recycling has been conducted in Turkey in an industrial zone that is government-regulated and leased to private companies. This zone is situated along the coast of

Aliaga, located 50 kilometres north of Izmir, on the Aegean coastline of Turkey. The ship recycling facilities are established on a peninsula and are located in close proximity to a petrochemical complex. Additionally, steelworks that primarily utilise recycled iron and steel, procured primarily from ship recyclers, are situated approximately 15 kilometres south of the peninsula (Neşer, 2012)

The state of the shipbreaking yards in Turkey has undergone improvement following the publication of a report by GREENPEACE that brought attention to the environmental and health hazards present in the Turkish ship recycling industry, specifically in the Aliaga region. The report critiqued the management of hazardous waste in the region, leading to a call for improvement (GREENPEACE, 2002). This report has led to improvements in the long term with the actions taken by both government and yards themselves. Better hazardous waste management facilities were built and have served the Turkish ship recycling industry since then (Gunbeyaz, 2019)

On the other hand, significant incidents have also occurred in Turkey's ship recycling business in the previous ten months, which has resulted in the loss of hundreds of jobs. Both yards are on the EU's list of permitted ship recycling operations, and both employees died due to their injuries in different yards. As a result of the recent incidents, there has been heightened concern about the working conditions in Aliaga, particularly the handling of hazardous wastes downstream and the lack of openness on occupational illnesses that sicken the workers there. A total of 47 occupational deaths have been documented in Aliaa since 1992 when a massive explosion claimed the lives of seven employees on plot 17 (NGO, 2022).

According to Istanbul Health and Safety Labour Watch, the factors contributing to accidents have remained consistent throughout the previous 30 years. On the other hand, workers might become ill and die from occupational illnesses years after being exposed to dangerous substances. The incidence of cancer in Aliaga is significantly greater than the national average in Turkey. Despite this, shipbreaking yard stakeholders continue to assert that no occupational illnesses are present at their facilities. The government does not consider violations of worker health and illegal practices in the handling and disposal of hazardous substances, such as asbestos, in the ship recycling industry.

This disconnects between the reported health risks and the claims of industry stakeholders highlights the need for a systematic approach to evaluating safety and environmental practices in ship recycling. In this context, it is essential to review existing ship recycling methods to understand their implications for worker health, environmental protection, and regulatory compliance.

2.2.2 Review of Ship Recycling Methodology

In their operation, ship recycling yards in several countries and the rest of the globe implement different ship recycling methods. Ship recycling methods are primarily similar: cutting vessel parts and dismantling further to the buyer's specifications. The primary difference is the type of docking used during the service, mainly on the yard's position.

2.2.2.1 Beaching

The term "beaching" refers to the procedure of decommissioning ships in the intertidal zone, characterized as the area of shoreline subject to tidal fluctuations. This method of ship demolition involves grounding the vessel in the tidal zone, where it can then undergo the process of disassembling, leading to the recovery of valuable components and eventual scrapping (Jain et al., 2017). Beaching is the most common method in South Asia (Figure 2.6). Approximately two-thirds of the global capacity for ship recycling at the end-of-life stage is estimated to take place on beaches, making it the dominant method in the present day. The prevalence of beaching as a ship recycling practice highlights the need for improved regulations and guidelines to address the environmental and health risks associated with this approach (LR, 2011). Approximately 70–90% of the global ship recycling capacity in gross tonnage terms is concentrated in India, Bangladesh, and Pakistan, where the beaching method is widely practiced (World Bank, 2010). According to NGO’s reports, 469 ships were beached (73% of total number) in 2015, 641 ships were beached (62.5% of total) in 2014, 645 ships (71% of the total) were beached in 2013, 922 ships were beached (68% of total) in 2012 (NGO Ship Breaking Platform, 2014 2013a, NGO Ship Breaking Platform, 2015, NGO Ship Breaking Platform, 2016 2013a, NGO Ship Breaking Platform, 2015, NGO Ship Breaking Platform, 2016). Although there is a decrease in the number of the ships that were beached compared to previous years, the percentage remains the same. In comparison, Turkey use a concrete beaching method, also known as the landing method, which mitigates several environmental and safety concerns associated with beaching. In this approach, ships are brought onto concrete platforms or hard surfaces near the shore instead of directly onto a natural beach (Turkish Ship Dismantling Association, 2019).

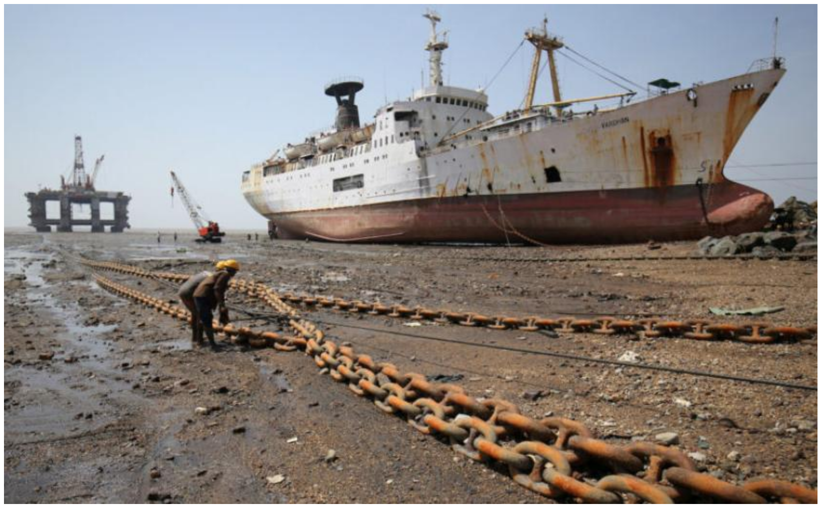


Figure 2. 6: Beaching method in Indian ship recycling yard

2.2.2.2 Slipway

The slipway method, also referred to as the landing or non-tidal beaching approach, shares several analogous features with the traditional beaching method in the process of ship recycling. This approach involves the utilisation of slipways, or inclined platforms, for supporting and launching vessels into the water, as well as for hauling them out of the water for the purpose of demolition and scrapping (LR, 2011). The main difference between the slipway method is that the infrastructure or constructed pier on the landing zone, the ground is commonly concrete, and there are more measures to prevent pollution than the beaching method). In the slipway, or can also be referred to as with landing method, the ship is docked at the shipyard's slipway area, which mostly starts lower than the sea and has a low inclining angle. This method is mainly used in Turkey and some ship recycling yards in the EU, where there is no tidal difference or very minimal.

2.2.2.3 Quayside

The Quayside (also referred to as Alongside) method is mainly used in China, Belgium, and the United States. The ship is berthed on the pier and shipyard and the process starts from the top and the approach is top to bottom in the vertical direction, in this method (LR, 2011). The ship's block is cut and removed till it reaches the double bottom, and the de-ballasting procedure is carried out with care to ensure that no ballast leaks into the water. Depending on the yard's capacities, the remaining double bottom, "canoe," either lifted to the land for further cutting or transferred to the dry dock (LR, 2011).

2.2.2.4 Dry-Dock

In this method, end of life ship is taken in a drydock of the yard. This method is often considered the safer and cleanest ship recycling method compared to other alternatives. The risk of polluting the environment stays low because all the contaminants in the ship stay in the drydock. Once the recycling procedure is done, the dock is cleaned to prepare it for the arrival of the next end-of-life vessel to be recycled (LR, 2011).

While the dry-dock method is widely regarded as one of the safest and most environmentally friendly approaches, its implementation can be costly and resource-intensive, limiting its adoption in many developing countries. Given the diversity of practices across regions and their varying impacts on safety, environmental sustainability, and economic feasibility, it is crucial to analyse ship recycling processes systematically. The next section below introduces the tools and frameworks used to evaluate and improve ship recycling practices, providing a foundation for identifying safer and more sustainable methods.

2.3 Reviews Ship Recycling Processes and Tools

Cutting is the primary activity in ship recycling. Several tools have been used in order to perform the cutting process. The most common tool is oxyfuel cutting used by traditional ship recycling yards. Some of the advanced yards use high-level technologies, which will be described below.

2.3.1 Oxyfuel cutting.

Oxyfuel cutting, a method of thermal cutting, involves the combination of oxygen and one of several fuel gases such as acetylene, propane, MAPP, propylene, or natural gas. This process is used to effectively cut through various materials. Since its' operational flexibility in terms of having a broad range of cutting thickness range from 0.5 mm to 250 mm and the low cost of equipment, it is the most widely used system in the industry. Cutting speed and cutting quality can be enhanced by improving the fuel gas and nozzle design (TWI Global, nd). The figure 2.7 below Illustrates the oxyfuel cutting process. The utilisation of a combination of fuel gas and oxygen in the oxyfuel cutting process is directed towards preheating the material, typically metal, to a temperature range of 700°C to 900°C, which is the ignition temperature for steel. It is essential to consider that the melting temperature of the material must exceed the ignition temperature for this method to be effective. Subsequently, a stream of pure oxygen is directed towards the preheated area, causing a puncture in the material and facilitating the cutting process.

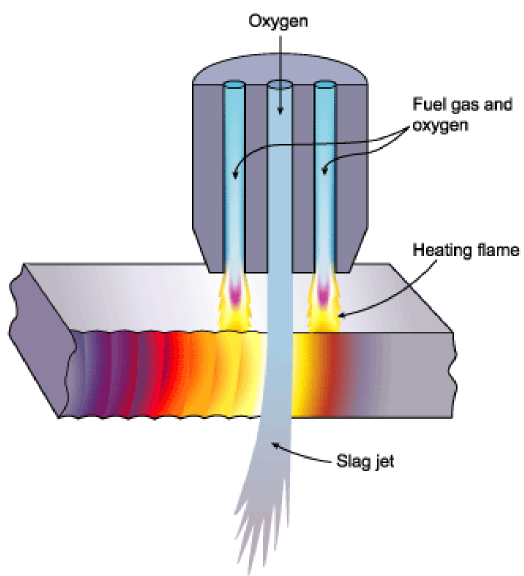


Figure 2. 7: Diagram of the oxyacetylene cutting process (TWI-Global)

In production-focused industries quality of the cut is very important. However, in the recycling, the quality of the cut is not necessary as the steel will end up in the steel mill and furnace. For the ship recycling industry, cutting speed is an essential factor. Cutting speed will affect two elements: productivity in the primary and secondary cutting zones and labour costs. The cutting speed is dependent on three main factors: choice of fuel gas, purity of oxygen, and type of Equipment (torch, nozzle). In the ship recycling industry, acetylene, propane, and natural gas are frequently utilised as fuel gases. While natural gas and propane possess lower flame temperatures compared to the maximum flame temperature of acetylene, this results in longer heating and piercing times. Nevertheless, the overall speed of the process remains largely comparable with the use of each gas. The portability of oxyfuel cutting equipment is a crucial requirement for the operations in ship recycling yards. The oxyfuel cutting kit comprises oxygen and fuel bottles, pressure regulators, flashback arresters (not commonly used in South Asia yards), torch itself, and cutting nozzle (Weldability, 2007). As mentioned before, oxy-fuel cutting is cheap, simple, and easy to use the method.

2.3.2 Diamond Wire Cutting System

The Diamond Wire Cutting System (DWCS) is an apparatus that enables cutting processes both above and below water, as depicted in Figure 2.8. It can be utilised in the cutting of jacket legs, piles, and diagonal members. Installation can be carried out through the use of divers or remotely operated vehicles (ROVs) for underwater operations. The system is comprised of a steel clamping unit and a diamond wire cutter. The tool is designed to securely hold the object to be cut during the cutting process. The cutting wire consists of a steel wire of approximately 6.35mm in diameter connected to a series of steel rings, which include diamonds spaced equidistantly at 25.4mm intervals. The wire rotates along the circumference of the frame, resulting in the cutting of the target object. During the cutting process, it is important to regulate the wire-speed, working pressure, and flow rate of the DWCS (ICF International).

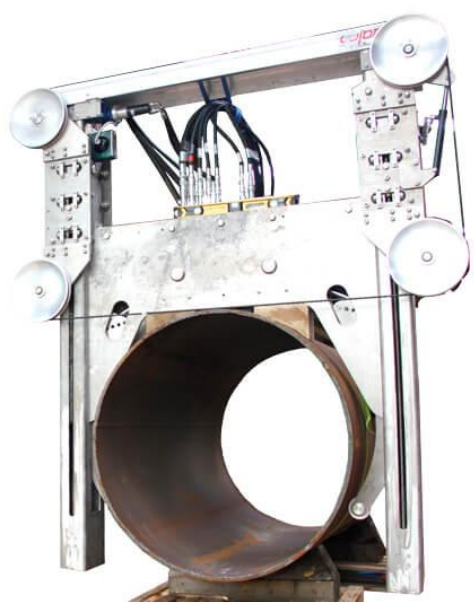


Figure 2. 8: An example of diamond wire cutting system (ndiver, 2022)

2.3.3 Mobile shear

Mobile shear (Figure 2.9) is one cutting technology consisting of metal jaws, and it is connected to the excavator. One of the company's manufacturers is Allied-Gator, and the type which is suitable for ship/ platform decommissioning is model MTR 160 S. The MTR 160 S weighs approximately 44,000 lbs.*, will fit 110 ton/220,000 pound and larger carriers in the second member (boom-mounted) configuration. The MTR 160 delivers the most real-world cutting force of any mobile shear. The MTR 160 has 360° continual rotation and a cycle time of fewer than 4 seconds close and 5 seconds open, making it the fastest cycling mobile shear of its size on the market.

Figure 2. 9: MTR 160 S decommissioning a platform off the coast of Norway (Alliegator, 2021)

The Average Yearly Operating Cost for an MTR 160 S model, subject to heavy use applications (like decommissioning of offshore oil platforms and ship cutting), ranges between $50,000 - USD 55,000 per year. The data used to reach this Average Yearly Operating Cost comes from historical analysis of actual units and includes all maintenance costs and wear part consumption. The service life of an MTR 160 S unit at this point exceeds 15 years (Approx. 20 years).

While equipment such as the MTR 160 S plays a vital role in improving efficiency and reducing long-term operational costs, the ship recycling process remains inherently hazardous. Beyond the financial considerations, the dismantling of end-of-life vessels exposes workers and the surrounding environment to significant risks. Understanding the types of hazards involved is crucial for developing effective safety measures and ensuring compliance with environmental and occupational health standards.

2.4 Hazard Involved in Ship Recycling Procedure

Despite ship recycling being viewed as an environmentally favourable option for the disposal of obsolete ships, it remains associated with hazards to human health, safety, and the environment during the ship recycling process, which might lead to accidents, injuries, or pollution of the environment (Garmer et al., 2015). In developing countries, safety measures during ship recycling activities are often insufficient, leading to elevated rates of accidents including explosions, falls from heights, and toxicity. Furthermore, long-term negative consequences such as exposure to hazardous materials highlight the hazardous nature of the operating environment in the ship recycling industry. (Z. Du, et. al., 208).

2.4.1 Key Hazards in Ship Recycling Identified by the ILO

The International Labour Organisation (ILO) outlines several hazards in ship recycling, emphasizing the need for strict safety protocols and protective measures to safeguard workers and the environment (ILO, 2004):

- Exposure to Hazardous Substances:
  Workers often handle toxic materials such as asbestos, lead, polychlorinated biphenyls (PCBs), and heavy metals, which can cause respiratory and other health issues.
- Fire and Explosion Risks:
  Residual fuels, oils, and gases within tanks and pipelines pose serious fire and explosion risks, especially if ships are not thoroughly cleaned before dismantling.
- Physical Injuries:
  Workers are at risk of falls from heights, slips, and injuries from handling heavy materials. Improper lifting techniques or lack of equipment often lead to musculoskeletal injuries.
- Confined Spaces:
  Workers entering enclosed areas like tanks and holds face risks of toxic fumes and oxygen deficiency, increasing the likelihood of asphyxiation.
- Falling Objects:
  Ship dismantling involves cutting large sections, leading to falling objects and debris that pose risks to workers if proper controls are not in place.
- Noise and Vibration:
  The use of cutting and hammering tools subjects' workers to high noise levels and vibration, potentially causing hearing loss and nerve damage.
- Chemical Burns:
  Solvents, acids, and chemicals used in cleaning and cutting can cause burns if proper protective equipment is not worn.
- Electrocution:

Power tools and welding equipment increase the risk of electrocution, especially in damp environments.

- Heat Stress:
  Ship dismantling, often done outdoors, exposes workers to high temperatures that can lead to heat stress, especially in confined spaces.
- Ergonomic Hazards:
  Repetitive motions, awkward postures, and excessive exertion are common, leading to musculoskeletal disorders.

Implementing strict safety protocols, training, and personal protective equipment (PPE) are essential to mitigate these hazards in line with ILO guidelines.

2.4.2 Hazardous Waste

The process of ship recycling results in the production of ferrous, brass, aluminum, copper, and other alloys, which are collected by vendors and sold on the scrap metal market. Other metallic resources, such as girders, structural components, pipes, beams, angles, and channels, recovered from dismantled ships are also sold promptly in their existing condition. In addition to metals, various shipboard recyclable materials also have a market value. Typical items include chandeliers, wood furnishings, door panels/frames, and kitchen equipment. Saleable items include appliances (refrigerators/washers), glass wool (insulating material), oils, lead-acid batteries, and machinery (engines/parts).

Shipbreaking wastes are classed as hazardous or non-hazardous. Breakable glass, broken floor tiles, polymeric trash, broken (non-asbestos) insulating materials are examples of non-hazardous waste. In addition to solid garbage, ammonia, CFCs from air conditioners, and combustible gases can be present in the pipes of oil tankers and LPG or LNG carriers. However, no genuine statistics on these wastes exist. Because the components of a ship might vary depending on its purpose, the waste generated by deconstruction can likewise vary. The hazardous waste stream from shipbreaking includes matrices that cannot be recovered or reclaimed owing to their characteristics or contamination. Thus, the following Table 2.1 shows the type of waste stream from the ship which can leads to pollutions.

Table 2. 1: Pollutants that can seep out of the waste material and leach into the surrounding environment (SHIPDISMANTL, 2009)

No	Waste Streams	What may be leached?
1	Asbestos	PCBs, PAHs,
2	Poly chlorinated biphenyls	PCBs, PAHs,
3	Oils and Fuels	Ni, As, Oil and Grease
4	Paints and Coatings	Cr, Pd, Zn, Cd, TBT, As, Ni and Solvents
5	Metals	Cr, Pd, Zn, Cd, TBT, Hg, As and Ni
6	Bilge and Ballast Water	Oil and Grease, Heavy Metal like Cr, Pd, Zn, Cd, TBT, As, Ni
7	Other Hazardous Materials	PAHs, PCBs, Petroleum Products, Oil and Grease

The presence of these hazardous waste streams highlights the significant environmental and health risks associated with ship recycling activities. Without proper handling and disposal, these pollutants can contaminate surrounding ecosystems and pose severe threats to workers and nearby communities. To mitigate these risks, a robust regulatory framework and international conventions are essential to ensure safe and sustainable ship recycling practices. The following section reviews the key regulations and frameworks governing the industry, outlining how they address hazardous materials and promote compliance among ship recycling facilities.

2.5 Regulatory and Normative Framework in the Ship Recycling Industry

The negative images of the industry, as mentioned above, forced the regulators to act and three conventions were developed to regulate the activity of the ship recycling facilities.

2.5.1 Basel Convention

To mitigate the risk of hazardous ships being dismantled in their waters, developing countries are obligated to adhere to the provisions outlined in the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes. However, these countries often face legal ambiguity in their implementation of the convention.

The Basel Convention, in particular, aims to curb the uncontrolled transboundary movement and disposal of hazardous waste, including instances where industrialized countries illegally dump such waste in developing nations. This is to ensure that hazardous waste is handled in a manner that minimises the risk to human health and the environment (Basel Convention, 2022)

However, The Basel Convention redefines existing principles of international environmental law, such as the 'polluter pays principle' and the 'proximity principle', within the context of a new overarching principle specific to toxic waste, called 'environmentally sound management (ESM). The Basel Convention's flexibility, in particular, demonstrates that it was intended to address the specific sort of hazardous waste transfers that happen whenever a ship is sold to be recycled in a developing country.

2.5.2 Hong Kong Convention

The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (HKC) is a landmark treaty established by the International Maritime Organization (IMO) to regulate the entire lifecycle of ships, from design and construction to operation and eventual recycling. Adopted in May 2009, the HKC sets out comprehensive requirements to ensure that ship recycling activities are carried out in a safe, environmentally responsible, and socially sustainable manner. It specifically addresses hazardous material management, safe working practices, and environmental safeguards within recycling facilities (IMO, 2009).

Compared to earlier frameworks such as the Basel Convention, which primarily focused on the transboundary movement of hazardous waste, the HKC provides more detailed, sector-specific guidance for the ship recycling industry. It introduces mandatory provisions, including the requirement for each vessel to maintain an Inventory of Hazardous Materials (IHM) throughout its operational life. This inventory facilitates safer dismantling and proper disposal of hazardous substances during recycling (IMO, 2019; BIMCO, 2023).

For the convention to enter into force, it required ratification by at least 15 states, collectively representing 40% of the world’s merchant shipping gross tonnage and 3% of the global ship recycling volume. A major breakthrough occurred in 2023, when India’s ratification provided the final capacity threshold needed for the convention’s activation. India’s commitment was particularly significant due to its prominent role as one of the largest ship recycling nations (Seatrade Maritime News, 2021; IMO, 2023).

Following this milestone, the IMO confirmed that the HKC officially entered into force on 26 June 2025 (IMO, 2025a). From this date onward, all signatory countries are required to comply with its provisions, marking a new era for global ship recycling. The HKC's implementation is expected to harmonise global practices, improving worker safety, reducing environmental harm, and creating a unified regulatory framework for one of the world's most hazardous industries (Lloyd's Register, 2025).

2.5.3 European Ship Recycling Regulation

The European Union's Ship Recycling Regulation was introduced in 2013 with the goal of strengthening the standards set by the Hong Kong Convention (HKC) on ship recycling. The secondary objective of this regulation was to facilitate the process of ratifying the HKC (Moncayo, 2016). The implementation of this regulation took place on December 30th, 2013, and the most recent implementation date was December 31st, 2018 (Jain, 2017 2013b).

The regulation applies to all ships that fly the flag of an EU member state as well as to ships that make a call or anchor at EU ports. This means that ships that are registered under the jurisdiction of an EU member state and ships that visit EU ports must comply with the requirements outlined in the Ship Recycling Regulation.

It is important to note that the EU's Ship Recycling Regulation was created with the intention of promoting environmentally friendly and safe ship recycling practices. The regulation covers a wide range of topics including ship design, operation, and decommissioning, all with the aim of reducing the negative impact of ship recycling on the environment and human health (Alcaide, 2017).

While the EU Ship Recycling Regulation has set a strong benchmark for sustainable and safe practices, its implementation and impact vary across regions. In many developing countries, including Indonesia, ship recycling practices are influenced by different economic, social, and regulatory contexts. Understanding the current state of the Indonesian ship recycling industry is essential to identify gaps, challenges, and opportunities for improvement in aligning with international standards. The following section provides an overview of Indonesia's ship recycling industry, including its scale, practices, and regulatory environment.

2.6 Indonesian Ship Recycling Industry Overview

As an archipelago state, the maritime sector is vital to Indonesia's growth, and as such, Indonesia maintains a significant fleet of ships. However, in general, Indonesia's current ship recycling industry does not meet the standards of existing regulations. It is harmful to the environment, but it is also hazardous to the safety of the involved workers. Ship recycling in Indonesia are mainly located on Madura Island (Fariya et al., 2016). Ship recycling is particularly essential for Indonesia since they now run a vast fleet of aging boats, most of which are scheduled to be retired shortly, shown in Figure 2.10:

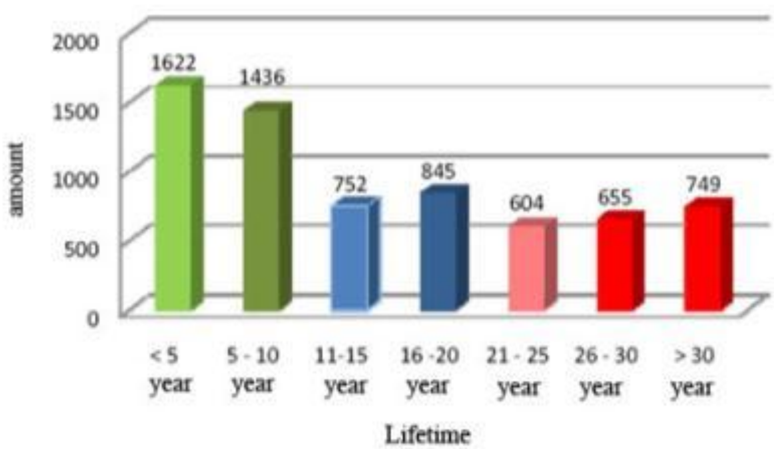


Figure 2. 10: The Distribution of ship lifetime in Indonesia (BKI, 2014)

Similarly, it can be seen that from the distribution of the number of ships above, the amount of ships older than 25 years old is 1.404 ships (21%). It is mostly possible that older ships will be recycled.

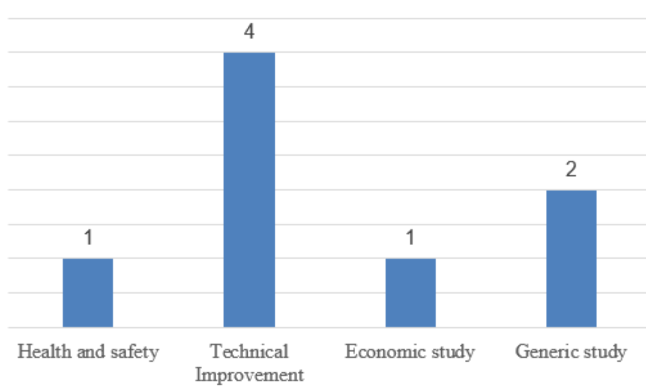


Figure 2. 11: Areas focused on the current research of Indonesian ship recycling

Even though this business has an enormous potential market, research in this area is minimal. The summary of current research about Indonesian Ship Recycling can be shown from the graph (Figure 2.11). The research mainly focuses on technical problems and solutions for the industry which can be applied directly, such as the design of a ship recycling yard in Tanggamus - Lampung, which has the capacity to recycle ships with a maximum weight of 30,000 DWT, would meet environmental and International Maritime Organisation (IMO) regulations. All activities conducted within the yard would be in compliance with these regulations to prevent any harmful or hazardous waste from polluting the nearby shoreline. This would be achieved by implementing a new layout and providing necessary facilities and procedures. (Sunaryo & Pahalatua, 2015). A similar study was conducted in 2016 to develop a sustainable ship recycling yard in Madura Island. This study shows that the slipway docking method, dry ice de-coating, oxy-acetylene cutting method, and crawler crane as material handling is suitable for the Indonesian Ship Recycling Industry. The activity of separating hazardous materials and their disposal sites into layouts must be prioritized as those activities are not considered (Fariya, et.al., 2019). However, in economic side, the ship recycling industry in Indonesia are worth doing because it has Internal Return value 97% (Akriananta, 2017).

On the other hand, a study about the trade-off between the shipbreaking industry's loss and gain shows the involvement of shipbreakers and the Government to maximize profit while minimising environmental damage and human danger. The reference scenarios will be the greatest and lowest levels of willingness to process hazardous chemicals, as well as the amount of investment in health and safety infrastructure (Kusumaningdyah, 2002). The investigation of these regulations shows that the legal framework to implement ship recycling regulations is in place. However, these regulations have several gaps. The most critical gap is the guide to the ship recycling facilities from the Indonesian Government. Currently, Indonesian yard owners do not get any support from the Indonesian Government as there are conflicting ideas about ship recycling on the Government-side.

There is currently a need for expertise in the Government or the related ministries to ratify IMO-Hongkong Convention fully. Nevertheless, the Ministry of Transport and the Ministry of Industry support the industry as there is a need for around a 7-million-ton steel annually. Currently, Indonesia can fulfill just 5 million tons through importing from other countries. On the other hand, the Ministry of Environment is totally against the ship recycling industry because of the industry's negative impact on the environment. Therefore, there is a disagreement between ministries in Indonesia towards the ship recycling industry. As a result of this disagreement, the ship recycling business is not legal in Indonesia. Some ship recycling yards in Indonesia are conducting this business entirely off the record.

Another challenge for the ship recycling industry in Indonesia is importing ships to Indonesia. Regulation of the Minister of Trade import no. 76 - 2019, which stated to ban importing any old ship above 30 years. Even though this rule is in force for operation, not recycling, it impacts the business as ship recycling yards need to purchase these ships as it is for operation and then scrap them as it is not an official business.

In conclusion, the ship recycling industry has legislative barriers to overcome before growing into a full-scale industry. The Indonesian Government needs support to overcome these challenges, and there is a need to develop a roadmap for the Government. This roadmap will be developed as part of this project and submitted to the Indonesian Government for review

2.6.1 Economic Impacts of the Indonesia Ship Recycling Industry and Potential Contribution to Economic Development

Due to the covert nature of the ship recycling industry, which operates outside of official records, it poses a challenge to gather comprehensive data on the economic impact of ship recycling on local, regional, and national levels. Presently, there is a lack of official information regarding the exact number of ships that have undergone recycling processes in Indonesia. Based on the surveys conducted at the "unofficial ship recycling yards" in Madura Island, it is estimated that approximately around 23,000 GT (roughly around ten units) of ships of various types being recycled every year, without clear identity who were the owners of the ships had been recycled because there is not any data being recorded. The ships to be recycled come from all over Indonesia, including Papua, Sulawesi, and Kalimantan. The sizes and types of ships vary, ranging from barges to oil tankers, fishing vessels, general cargo, etc., from less than 500 tonnes to 2,000 tonnes of weight.

Almost all ship parts can be sold beside the steel plate from the ship's structure, such as pipes, engines, pumps, motors, propellers, and electric wires from cables. At present, there is a lack of clear and definitive data regarding the business operations involved in ship recycling activities in both Jakarta and Madura Island. However, through information obtained from the informal survey, there are various ways of distributing the ship recycling "products" dependent on the types of the "products ." Usually, the products are not directly sold by the yards to the end-users but through specialised brokers or intermediary buyers, who are always present around the ship recycling yards. The brokers sell the products to the resellers, or in case of steel products that are not suitable to be reused, they are sold to the steel mills. Good quality straight steel plates are sold to ship repair yards, engines, and ship equipment is sold to ship owners who want to replace their worn-out engines or equipment; there is also a particular buyer for ship accessories to be sold to ship owners or even restaurants.

Not all of the steel obtained from the ship scrap are sent to the steel mills; straight steel plates and pipes are bought by collectors for ship repairing, engines and other ship equipment which are still in good condition are directly sold for reused (the buyers are ship owners or resellers of used ship components). Only ship parts that cannot be reused or are not in good condition are sold to brokers to steel mills and transported using trucks. The price of scrapped steel is around IDR 3,500 to IDR 5,000 per kg. Profit earned from each ship varies dependent on the size and type of ship, ranging from hundreds of millions to some billion rupiahs (1,000,000 IDR is around 55 GBP).

The number of individuals employed in ship recycling yards varies based on the size of the vessel, with a range of 15 to 20 employees being present during the process. The workers usually consist of those specialised in ship machinery and system dismantling; ship structure breaking; liquid draining; decorating;

crane operators etc., come from local villages. Workers' wages range from IDR 250,000 for structure and machinery cutter to IDR 90,000 for plate and tank cleaner.

The workers in traditional ship recycling yards, which operate unofficially, do not have permanent employment status. They are paid on a daily basis and typically hail from the surrounding area. The number of these workers is contingent upon the availability of work and the specific nature and size of the vessel undergoing recycling. For instance, in the case of a "yard" recycling a 1,000 Dwt general cargo ship, it is estimated that there will be approximately 15 to 20 workers employed.

The workers' wages range from IDR 250,000 for block structure, pipes and machinery cutting, dismantling, and crane operator, to IDR 90,000 for plate cutting and cable stripping per day.

The current information on ship recycling is quite limited; if the ship recycling industry can comply with international norms, Indonesia can become a global centre for green ship recycling, which will greatly contribute to the economy. At present, ship recycling yards in South Asia are making efforts to comply with the regulations set forth by the Hong Kong Convention and the European Union. However, there remains a significant amount of time before these efforts will be fully realized. Furthermore, the EU's ship recycling regulations necessitate that recycling yards operate from enclosed structures, thereby prohibiting the use of the beaching method. Regulation introduced the "European List of Ship Recyclers" that EU-flagged ships must be sent to these listed "approved" yards. (EC, 2016b). The European Commission accepted the first edition of the European list of ship recycling yards in December of 2016. (EC, 2016c). As Indonesia already has the facilities to comply with European Ship Recycling Regulation, it can become the centre for ship recycling considering the opportunity in the market and the geological position of Indonesia.

2.6.2 Potential of Ship Recycling Industry in Indonesia

In 2005, The Cabotage Principle (Presidential Instruction No. 5, 2005) was introduced by Indonesian Government to incentivize an increase in the number of merchant fleets in Indonesia, which led to an increase of fleet from 6041 units in 2005 to 13,000 units in 2013 and 23823 units in 2017. (INSA, 2018). However, most of these imported ships are obsolete and must be replaced with new ones. Ministry of Industry's report in 2018 states that 21% of these ships are 25 years and older, totaling about 25 million GT (Ministry of Industry, 2018), 9% are between 20 to 25 years, the fleet is dominated by barges that consist of almost 1/3 of the total fleet. (Roesdianto/IPERINDO, 2018). With approximately 1250 ships requiring recycling over the next 5 years, the need for a sustainable ship recycling industry becomes apparent. Data provided by Indonesia's National Ship-owners Association indicates that among the nation's 13,000 merchant ships, approximately 5,000 are comprised of container ships and oil tankers, ranging in size from 3,000 to 50,000 dwt. It is estimated that 50% of these vessels fall within the 10,000 to 30,000 dwt range (Sunaryo et al., 2015). Recycling these ships in Indonesia will significantly benefit Indonesia at local, regional, and national levels. For example, the output of the Bangladesh ship recycling Industry is worth £550 million on average annually, and the Industry creates 25000-40000 jobs at its peak directly and many more through the side industries. Similar success can be achieved in the medium term (10 years) in Indonesia if the Government can support the ship recyclers and investors with guidelines, legislation, and financial incentives.

Moreover, the ship recycling industry can also support the development of Indonesia by providing the necessary materials for the ongoing constructions, projects, and investments, hence supporting the growth. According to the International Trade Administration of USA (ITA, 2019), Indonesia ranks as the tenth country (2017 data, 14th in 2018 in total imports, and 6th in net imports) amongst the largest steel importers. In 2017, Indonesia Imported 11.4 million metric tons while importing 11.6 million metric tons of steel in 2018 from over 85 countries and territories (ITA, 2019). In 2017, Indonesia imported 80.5% of the total steel needed (the highest import rate was 89.7% in 2012), but in 2017 also, Indonesia's steel production reached its peak with 5.2 million metric tons produced.

Based on the data from the Ministry of Industry due to the massive development in infrastructure projects in Indonesia, the need for steel nationwide is around 15 million tonnes per year. Regarding the Indonesia Iron and Steel Industry Association (IISIA), the demand is predicted to reach up to 21 million tonnes in 2025 (IISIA, 2017) (Figure 2.12). The construction industry uses 78% of the total steel, the major steel consuming Industry, followed by automotive with around 8% and Oil & Gas with 7%. In the meantime, 44% of the steel imports are flat products, 32% are semi-finished products, 15% are pipe and tube, and 4% in stainless steel (ITA, 2019). In last two years, price of this raw material has increased from USD450 to USD800 per ton due to lack of supply. The ship recycling sector can provide a solution for the need.

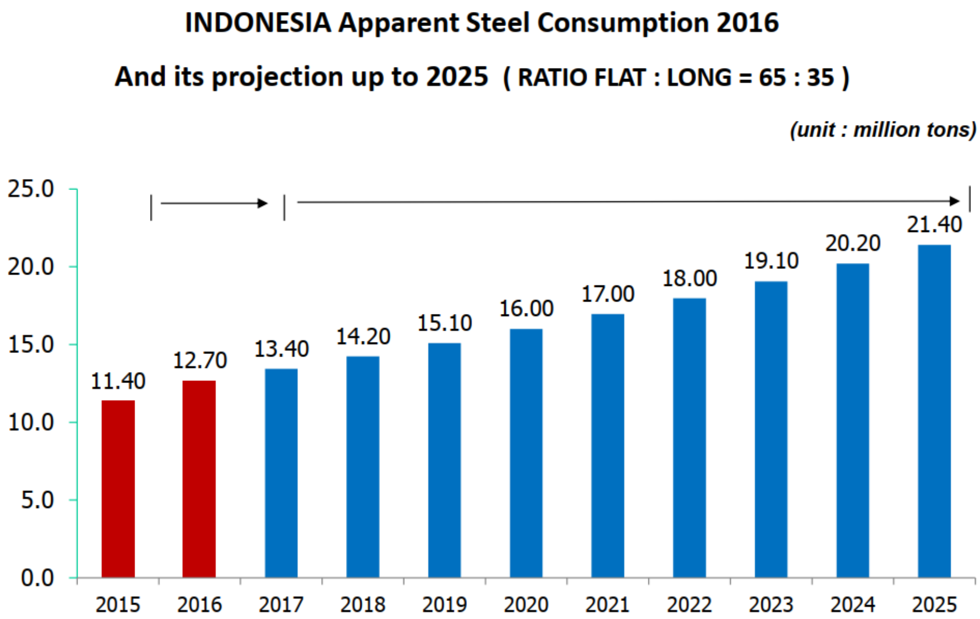


Figure 2. 12: Steel need expectation (IISIA, 2017)

The variety of materials, equipment, and gear that may be recovered from the old is considerable (Table 2.2), and have the possibility of reusing, repairing, remanufacturing, and recycling which is critical for developing nations since these materials may be reused in a variety of sectors; for example, ship metal could be rerolled/melted and used in construction. Equipment from ships (during refit or repair) or enterprises may also be reused (e.g., diesel generators to be used in factories). As a result, the ship recycling business contributes to the nation's economic growth in which it is situated.

Table 2. 2: Summary of the equipment on board a ship (modified from Gunbeyaz, Kurt, & Mckenna, 2018; The SFI Group System, 2001)

Section of the ship	**Valuable items**
Hull of the ship	Hull structure and Superstructure (steel) Structural bulkheads, decks (steel) Door, hatches, and scuttles, seats, supports, and masts (steel) Control surfaces

	Structural castings, Forgings, Fastenings
Equipment for cargo	Cargo machinery and equipment including systems loading/ discharging for vessel cargo, Cargo winches and hatches Cargo Handling Equipment Lifts and Lifting Appliances Portable Lifting Equipment
Equipment	Ship-specific tools, machinery, manoeuvring and navigational equipment Anchoring and communication equipment, Gyro`s, compass, antennas, displays, alarms, panels, con Radar Navigational Aids Propellers, Rudders, Stabilisers Anchor, Capstans Television, Radio & Satellite Communications
Equipment for accommodation and working environment	Equipment machinery and systems for lifesaving, accommodation, catering, sanitary systems. General Fittings Boats and Lifesaving Equipment Furnishing and Fittings Galley, Laundries & Workshop Equipment

	Accommodation & Medical Stores
Machinery Main Components	Primary components e.g main and auxiliary engines, propulsion plant, generator, and boilers Main Machinery Auxiliary Machinery Turbines Generators
Systems for Main Components of Machinery	Systems serving main machinery components, e.g. fuel, lubrication, exhaust, automation systems Fuel Service Systems Exhaust and air Supply Machinery Control Tanks
Common Systems	Ship systems, e.g. bilge and ballast, firefighting, and electrical distribution. Waste Disposal Electrical Power Distribution Equipment & Cabling Lighting Equipment Air Conditioning, Ventilation and Refrigeration Systems

As mentioned previously, the EU Ship Recycling Regulation provisions will alter the way the ship recycling business operates. EU Ship Recycling Regulation requires yards to “operate from build structures,” and ship with EU flag needs to be recycled in the approved list of ship recycling yards within the "European List of Ship Recyclers" (EC, 2016b). This is an excellent opportunity for Indonesia as Indonesia already has shipbuilding and ship repair yards and other necessary facilities to comply with European Ship Recycling Regulation. It can become the center for ship recycling considering the opportunity in the market and the geological position of Indonesia. The fate of the EU ships between 2015 and 2017 is demonstrated in the below graphic (Figure 2.13). Currently, the EU ships will not be beached as of the 1st of January 2019. As a solution, some companies prefer changing the ship's flag to non-EU flags and scrapping the vessel in the South Asian countries. Cash buyers are mainly used to conduct this operation to earn more end-of-life value from the ship to be scrapped.

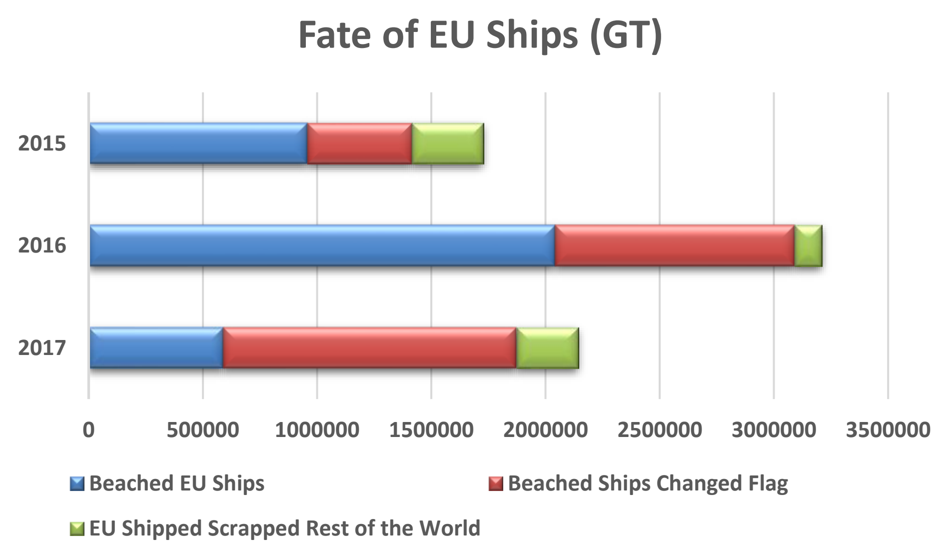


Figure 2. 13: Fate of EU Ships between 2015-2017 (Transport and Environment, 2018)

In addition, China has banned the export of waste in July 2017, including the ships and offshore assets. This decision will affect the future of the ship recycling industry, considering that China dismantled the 11 percent last year (NGO Ship Breaking Platform, 2017). Indonesia can replace this lost capacity by developing a safe and sustainable ship recycling industry and can attract shipping companies with corporate social responsibility. Additionally, Indonesia's geographical location provides an advantage due to its proximity to trade routes. Indonesia is surrounded by Asia and Australia continent.

Additionally, Indonesia is located in the Indian and Pacific Oceans center. Indonesia can become a berth for ships destined for these seas due to its geographical location. Indonesia wasters are already part of essential sea routes (Figure 2.14); therefore, it can be a suitable final destination for commercial vessels working around these routes. This strategy would also fit Indonesia's aim of becoming a World Maritime Axis as delivered by President Joko Widodo during the 9th East Asia summit in 2014 (Myanmar). Following this announcement, the Government of Indonesia has developed several projects to fulfill this ambition. Becoming a world-leading ship recycling center will also support this goal through financial and other benefits.

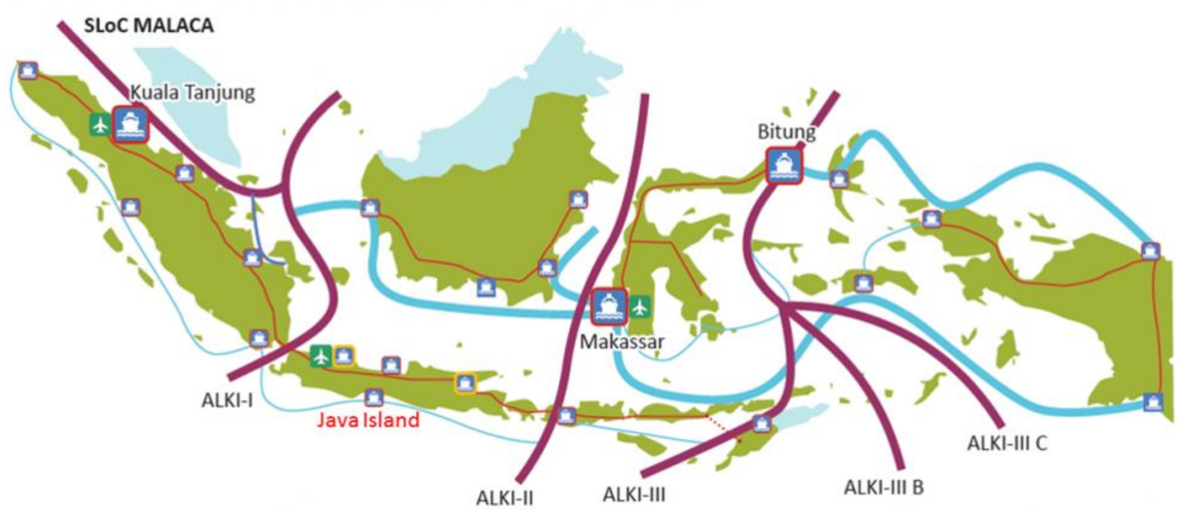


Figure 2. 14: Alur Laut Kepulauan Indonesia-ALKI (The Indonesian Institute, TII, 2016)

- ALKI I refers to the traverse of the South China Sea, Karimata Strait, Java Sea, and Sunda Strait.;
- ALKI II encompasses the traversal of the Sulawesi Sea, Makassar Strait, Flores Sea, and Lombok Strait.;
- ALKI III refers to the passage through the Pacific Ocean, Maluku Sea, Seram Sea, Banda Sea, Ombai Strait, and Sawu Sea.

As mentioned before, Indonesia already has the facilities and the capacity to recycle ships safely and sustainably. The shipyards in the country can be used to recycle the end-of-life vessels. Ministry of Industry states that the production capacity for new ships is 900,000 DWT per year, while the utilisation rate of the yards is only 60%. In the meantime, the capacity for ship repair in Indonesia is 12 million DWT per year, with a utilisation rate of 80%. Around 250 enterprises are focusing on shipbuilding, employing 250,000 people (indirectly 1,000,000 people). The distribution of these enterprises is demonstrated in Figure 2.15

Figure 2. 15: Distribution of Indonesia shipbuilding enterprises (IPERINDO, 2019)

The largest production capacity amongst these enterprises is 150,000 DWT Drydock (graving dock) which can be used for ship recycling operations while not utilised for shipbuilding operations. Most of these yards (56%) have a capacity of 500 GT, but six shipyards have a capacity between 10,000 to 50,000 GT. Meanwhile, there are three ship repair yards with a maximum of 100,000 GT and one with 100,000 GT capacity. In future project analysis, the utilisation of these yards as a ship recycling yard will be investigated, and these yards will be included as a case study in these studies.

2.6.3 Indonesian Ship Recycling Regulation

There are several national laws that relate to ship recycling. In this section, the requirements of these regulations are summarised.

2.6.3.1 Regulation of the Ministry of Transport Republic of Indonesia No. PM 29, year 2014 on the Prevention of Maritime environmental pollution. Summary of Chapter 51 – 56)

Chapter 51 establishes that international regulations apply to ships over 500 GT in international waters, as well as all ship recycling facilities, while ships over 100 GT and recycling facilities in Indonesian waters must follow national regulations. Compliance with these standards enables certification from the Director-General. Chapter 52 strictly prohibits the use of hazardous materials in ship recycling, requiring that ships maintain a record of such materials onboard and that shipowners prepare a safety-approved inventory. Preparations for recycling include safe handling of oils, chemicals, waste, and ballast water, with all necessary documents inspected before recycling begins. Chapter 53 stipulates that ship recycling can only occur at approved facilities with a comprehensive recycling strategy and permit. Chapter 54 designates ship safety officers to oversee the implementation of inspections and ensure compliance. Finally, Chapter 55 requires a detailed report to be submitted upon completion of recycling activities.

2.6.3.2 Circulation Letter No. 19/PK/DK/2019 on the Indonesian flagged ship recycling, as enforcement of Regulation of the Ministry of Transport Republic of Indonesia No. PM 29, the year 2014.

2.6.3.3 Shipping Law no. 17, 2008, chapter 241, and 242 on ship recycling

Chapter 241

- Requirements and location of ship recycling.

Chapter 242

- Ministry regulations on the environmental protection for ship recycling.

2.6.3.4 Government regulation No. 101 the year 2014 on the dangerous and poisonous wastes handling.

The regulation covered: definition, reduction, keeping, collection, transporting, making use of, treatment, staking, dumping, exception, transboundary, combating, contingency system, coaching, inspection, funding, sanction of dangerous and poisonous wastes.

The investigation of these regulations shows that the legal framework to implement ship recycling regulations is in place. However, these regulations have several gaps. The most critical gap is the guide to the ship recycling facilities from the Indonesian Government. Currently, Indonesian yard owners do not get any support from the Indonesian Government as there are conflicting ideas about ship recycling on the Government-side.

Currently, the transportation ministry fully adopted the Hong Kong Convention guideline in 2019. However, since there is no expertise in the Government or the related ministries, the overall requirements of the current regulation (Section 5.2.1) is a direct copy-paste of the Hong Kong convention. Moreover, the Indonesian government does not have an expert resource to handle this issue properly in any government body. Nevertheless, the Ministry of Transport and the Ministry of Industry support the industry as there is a need for around a 7-million-ton steel annually. Currently, Indonesia can fulfill just 5 million tons through importing from other countries.

On the other hand, the Ministry of Environment is totally against the ship recycling industry because of the industry's negative impact on the environment. Therefore, there is a disagreement between ministries in Indonesia towards the ship recycling industry. As a result of this disagreement, the ship recycling business is not legal in Indonesia. Yards in Indonesia (illegal ones in Madura or the legal shipbuilding yards that conduct recycling operations as a side business) are conducting this business entirely off the record. When interviewed, several yards (who cannot be named due to legal reasons) acknowledged conducting ship recycling operations. However, they do not accept it officially or advertise it as their business.

Another challenge for the ship recycling industry in Indonesia is importing ships to Indonesia. The rule states that Indonesia cannot import any old ship above 20 years. Even though this rule is in force for operation, not recycling, it impacts the business as ship recycling yards need to purchase these ships as it is for operation and then scrap them as it is not an official business.

In conclusion, the ship recycling industry has legislative barriers to overcome before growing into a full-scale industry. The Indonesian Government needs support to overcome these challenges, and there is a need to develop a roadmap for the Government. This roadmap will be developed as part of this project and submitted to the Indonesian Government for review.

Given these complex legal, environmental, and regulatory challenges, understanding how other regions and scholars have approached similar issues becomes essential. Academic research provides valuable insights into best practices, policy frameworks, and technological innovations that can guide the development of a sustainable ship recycling industry in Indonesia. The following section reviews existing academic literature on ship recycling, highlighting key themes, methodologies, and findings that can inform both policy development and practical implementation.

2.7 Review of Academic Research in Ship Recycling

The ship recycling industry's challenges are discussed to diagnose the core issues, in this section. These issues are also essential to identify the direction of this research. As shown in the figure 2.16, one of the most significant challenges facing the sector is the potential for health, safety, and environmental dangers involved with ship recycling operations. The ship recycling industry is accepted as one of the most dangerous industries globally by ILO due to the hazards associated with ship recycling. Studies demonstrate that occupational standards are hazardous, and yards are very dangerous. Workers in the yards are constantly at the risk of being exposed to various hazardous materials that are highly harmful to human health.

It is also noted that a single research paper can address multiple categories of these issues, reflecting the interlinked nature of health, safety, and environmental risks within the sector. Therefore, some studies may contribute insights to more than one area, underlining the multifaceted challenges that ship recycling presents.

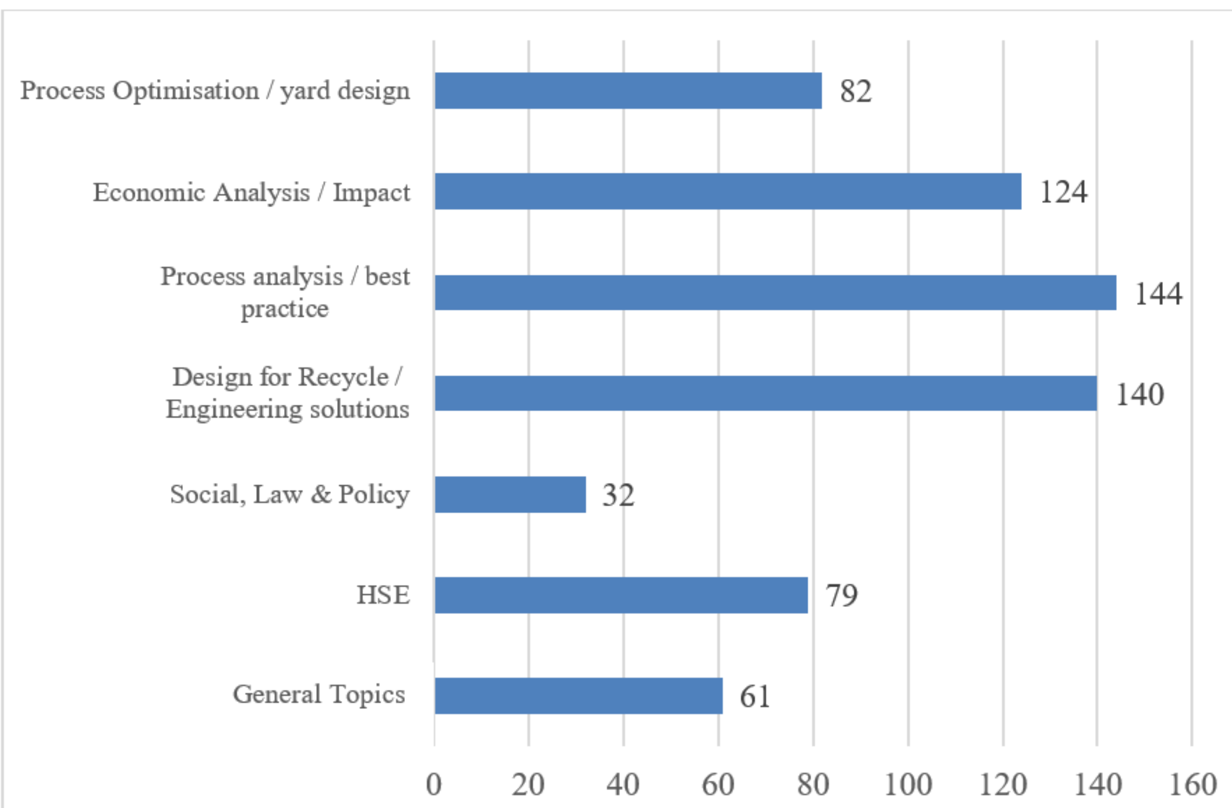


Figure 2. 16: Previous research about ship recycling

2.7.1 Process Analysis/ Best Practices

The papers in this category examine methods and best practices in ship recycling, including standard operating procedures, process improvements, quality control, and benchmarking against industry standards to increase safety, efficiency, and environmental performance.

Ship recycling industry is a critical sector that requires a comprehensive analysis of its processes, best practices, and adherence to safety and environmental standards. This review synthesises recent literature on methods and best practices in ship recycling, focusing on standard operating procedures, process improvements, quality control, and benchmarking against industry standards. The goal is to enhance safety, efficiency, and environmental performance in ship recycling operations. One of the foremost challenges in ship recycling is the management of hazardous materials. The dismantling of ships often releases toxic substances, including heavy metals, asbestos, and polychlorinated biphenyls (PCBs), which pose significant health risks to workers and environmental hazards (Du et al., 2018; Lin et al., 2022).

The International Maritime Organisation's Hong Kong Convention provides a framework for managing hazardous materials in ship recycling, emphasizing the need for compliance with stringent safety and environmental standards. However, many ship recycling yards, particularly in developing countries, struggle to meet these requirements due to inadequate infrastructure and regulatory oversight. This gap highlights the necessity for improved training and operational protocols to ensure that workers are equipped to handle hazardous materials safely (Gunbeyaz et al., 2019).

In terms of process improvements, the implementation of Material Flow Analysis (MFA) has been proposed as a tool to optimise recycling operations (Jain et al., 2017; Jain et al., 2016). MFA allows for a detailed understanding of material composition in end-of-life ships, which can lead to more efficient recycling processes and better hazardous waste management (Jain et al., 2016). By identifying the types and quantities of materials present, recycling yards can enhance their operational efficiency and reduce costs associated with waste disposal (Jain et al., 2017; Jain et al., 2016).

Furthermore, discrete event simulation has been utilised to assess the impact of the International Maritime Organisation's regulations on productivity in ship recycling yards, revealing that structured processes can significantly improve operational outcomes (Fariya et al., 2022). Quality control in ship recycling is paramount, as it directly influences both safety and environmental performance. The establishment of standard operating procedures (SOPs) is essential for ensuring that recycling practices adhere to international standards (Tola et al., 2023; Sunaryo et al., 2021). SOPs should encompass all phases of the recycling process, including preparation, deconstruction, and material stream management (Fariya et al., 2022; Tola et al., 2023). By standarsizing these processes, ship recycling yards can minimise risks associated with hazardous materials and improve overall safety for workers (Gunbeyaz et al., 2019; Tola et al., 2023).

Moreover, benchmarking against best practices in leading ship recycling nations can provide valuable insights into effective operational strategies and regulatory compliance (Sunaryo et al., 2021). The role of the circular economy in ship recycling is increasingly recognized as a means to enhance sustainability and resource efficiency (Steuer et al., 2021; Tola et al., 2023). The transition to a circular economy model involves rethinking waste management practices and promoting the reuse and recycling of materials extracted from end-of-life ships (Tola et al., 2023). This approach not only reduces environmental impacts but also creates economic opportunities within the recycling sector (Tola et al., 2023).

However, the successful implementation of circular economy principles requires collabouration among stakeholders, including ship owners, recycling yards, and regulatory bodies (Steuer et al., 2021; Tola et al., 2023). Environmental performance in ship recycling is closely linked to the adoption of eco-friendly technologies and practices. Recent studies have highlighted the potential of hybrid shipyard concepts that integrate green technologies into traditional recycling processes (Zainol et al., 2023). These innovations can help reduce the environmental footprint of ship recycling operations while maintaining competitiveness in the market (Zainol et al., 2023). Additionally, the development of eco-ship recycling industrial parks has been proposed as a strategy to enhance sustainability in the sector (Sunaryo & Aidane, 2022). Such initiatives can facilitate the sharing of resources and knowledge among recycling facilities, leading to improved environmental outcomes (Sunaryo & Aidane, 2022).

Despite the advancements in ship recycling practices, significant challenges remain. The lack of adequate occupational health and safety (OHS) standards continues to pose risks to workers in the industry (Gunbeyaz et al., 2019; Lin et al., 2022). Many ship recycling yards employ seasonal migrant workers who may lack the necessary training and awareness of safety protocols (Gunbeyaz et al., 2019). To address these issues, comprehensive training programs and safety regulations must be established to protect workers and ensure compliance with international standards (Gunbeyaz et al., 2019).

Furthermore, the economic pressures faced by ship recycling facilities often lead to compromises in safety and environmental practices, underscoring the need for a balanced approach that prioritizes both profitability and sustainability (Gunbeyaz et al., 2019). In conclusion, the ship recycling industry is at a crossroads, facing both challenges and opportunities in its quest for improved safety, efficiency, and environmental performance.

The integration of best practices, adherence to international regulations, and the adoption of innovative technologies are essential for transforming ship recycling into a sustainable and responsible industry. Future research should focus on developing comprehensive frameworks that address the multifaceted challenges of ship recycling, ensuring that the sector can meet the demands of a rapidly changing global landscape.

2.7.2 Economic Impact

The papers in this category analyse the financial and economic implications of ship recycling. This includes cost-benefit analysis, economic sustainability, market analysis for recycled materials, and the financial impact on local and global economies.

The economic impact of ship recycling is a multifaceted issue that encompasses financial implications, market dynamics, and sustainability considerations. This review synthesises recent research on the economic aspects of ship recycling, focusing on cost-benefit analyses, market analysis for recycled materials, and the broader financial impact on local and global economies. One of the primary economic considerations in ship recycling is the cost-benefit analysis associated with the dismantling process. Ship recycling can yield significant financial returns through the recovery of valuable materials, such as steel, copper, and aluminum, which constitute a large portion of a ship's weight (Steuer et al., 2021). The recovery value of materials from end-of-life ships is estimated to be between 85% to 95%, making ship recycling a potentially lucrative endeavor (Steuer et al., 2021).

However, the economic viability of recycling operations is often challenged by fluctuating market prices for scrap materials and the costs associated with adhering to environmental regulations (Solakivi et al., 2021; Lin et al., 2022). For instance, the implementation of the European Union's Ship Recycling Regulation has introduced stricter standards that, while beneficial for environmental sustainability, may increase operational costs for recycling facilities (Solakivi et al., 2021). This regulatory landscape necessitates a careful balance between compliance costs and the profitability of recycling operations. Market analysis for recycled materials reveals a complex interplay between supply and demand dynamics. The global demand for recycled materials, particularly in the steel industry, has been influenced by various factors, including economic growth, infrastructure development, and international trade policies (Rahman et al., 2016).

The COVID-19 pandemic has further disrupted traditional supply chains, leading to increased prices for scrap metal and prompting ship owners to consider recycling options in South Asian facilities, which often offer higher prices for dismantling ships (Rahman et al., 2021). This shift underscores the importance of understanding market trends and the competitive landscape in the ship recycling sector.

Countries like Indonesia are positioning themselves as potential alternatives to established recycling hubs in South Asia, driven by the prospect of stricter international regulations and the potential for economic development (Sunaryo et al., 2021). The financial impact of ship recycling extends beyond individual facilities to local and global economies. In regions where ship recycling is a significant industry, such as Bangladesh and India, the sector contributes to job creation and economic activity (Gunbeyaz et al., 2019)

However, the economic benefits must be weighed against the environmental and social costs associated with hazardous waste management and occupational health risks (Du et al., 2018). The reliance on informal and often unsafe recycling practices in some countries raises concerns about the long-term sustainability of the industry and its economic contributions (Lin et al., 2022). Therefore, fostering a more sustainable ship recycling industry requires investments in technology, training, and adherence to international standards to mitigate negative impacts while maximizing economic benefits (Hossain, 2018).

Moreover, the transition towards a circular economy presents both challenges and opportunities for the ship recycling industry. The concept of circularity emphasizes the importance of reusing and recycling materials to minimise waste and promote sustainability (Tola et al., 2023). Implementing circular economy principles in ship recycling can enhance economic sustainability by creating new markets for recycled materials and reducing dependence on virgin resources (Tola et al., 2023).

However, achieving this transition requires collabouration among stakeholders, including ship owners, recycling facilities, and regulatory bodies, to develop frameworks that support sustainable practices while ensuring economic viability (Tola et al., 2023). In conclusion, the economic impact of ship recycling is a complex interplay of financial returns, market dynamics, and sustainability considerations. While the potential for profitability exists through the recovery of valuable materials, the industry faces challenges related to regulatory compliance, market fluctuations, and environmental sustainability. Future research should focus on developing comprehensive economic models that account for these factors, enabling stakeholders to make informed decisions that balance economic growth with environmental responsibility.

2.7.3 Solutions Process Analysis / Best Practice

The papers in this category examine methods and best practices in ship recycling, including standard operating procedures, process improvements, quality control, and benchmarking against industry standards to increase safety, efficiency, and environmental performance.

This review critically evaluates the methodologies presented in the paper, drawing on relevant literature to contextualize the findings and highlight areas for further exploration. One of the key themes in the paper is the importance of standard operating procedures (SOPs) in ship recycling. SOPs are essential for ensuring that recycling practices adhere to safety and environmental regulations. The literature supports this assertion, indicating that well-defined SOPs can significantly reduce the risks associated with hazardous materials commonly found in ships, such as asbestos and heavy metals Du et al. (2018).

The findings of Gunbeyaz et al. (2019), who argue that the lack of adequate training and awareness among workers in ship recycling yards can lead to unsafe practices, underscoring the necessity of SOPs for worker safety and environmental protection. Process improvements are another critical focus of the paper. The integration of Material Flow Analysis (MFA) is highlighted as a tool for Optimising recycling processes. Jain et al (2017) demonstrate that MFA can help identify inefficiencies in the recycling process and facilitate better waste management practices. By implementing MFA, recycling yards can streamline operations, reduce costs, and enhance the recovery of valuable materials. This approach is particularly relevant in the context of the ship recycling industry, where the economic viability of operations is closely tied to the efficient recovery of materials (Jain et al., 2017).

Furthermore, Zhou et al (2013) emphasize that fostering a culture of safety awareness among workers can lead to improved safety behaviours and, consequently, better environmental outcomes. Quality control is another essential aspect discussed in the paper. The establishment of quality control measures is vital for ensuring that recycled materials meet industry standards. The literature indicates that rigorous quality control practices can enhance the marketability of recycled materials, thereby increasing the economic sustainability of ship recycling operations (Solakivi et al., 2021). For example, the European Ship Recycling Regulation mandates compliance with specific quality standards, which can help improve the competitiveness of recycling yards in the global market (Solakivi et al., 2021).

However, the paper could benefit from a more detailed exploration of the specific quality control measures that can be implemented in ship recycling yards, as well as their impact on operational efficiency and safety. Benchmarking against industry standards is another critical area addressed in the paper. The importance of benchmarking is underscored by the need for continuous improvement in ship recycling practices. By comparing their operations against best practices in leading ship recycling countries, facilities can identify gaps and implement necessary changes to enhance safety and efficiency (Gregson et al., 2011). The literature supports this notion, with studies indicating that benchmarking can lead to improved operational performance and compliance with international regulations (Tola et al., 2023).

However, the paper could further elabourate on the specific metrics and indicators that should be used for effective benchmarking in ship recycling. In conclusion, the paper "Solutions Process Analysis / Best Practice" provides valuable insights into the methods and best practices in ship recycling. It effectively highlights the importance of standard operating procedures, process improvements, quality control, and benchmarking against industry standards.

However, further exploration of specific quality control measures, detailed methodologies for benchmarking, and the integration of worker training programs could enhance the overall analysis. The synthesis of literature reinforces the need for a comprehensive approach to ship recycling that prioritizes safety, efficiency, and environmental performance.

2.7.4 Design for Recycle / Engineering Solutions

This category covers research on engineering approaches and design innovations that facilitate easier, safer, and more environmentally friendly ship recycling. This includes designing ships with materials and structures that reduce dismantling risks and waste.

One of the central themes of the paper is the necessity of integrating recycling considerations into the design phase of ships. Palomba et al. emphasize that the design phase must account for the implications of materials and structures on environmental emissions throughout the ship's lifecycle Palomba et al. (2022). This perspective aligns with the Hong Kong International Convention, which mandates that ship design should facilitate safe and efficient recycling. The literature indicates that incorporating recyclable materials and designing for disassembly can significantly reduce the environmental impact of ship dismantling (Fariya et al., 2022).

For instance, the use of lightweight materials can enhance energy efficiency during operation and simplify the recycling process at the end of the ship's life (Rahman et al., 2021). This approach not only minimises waste but also maximizes the recovery of valuable materials, thereby supporting a circular economy in the maritime sector. The paper also discusses the role of Material Flow Analysis (MFA) as a tool for improving ship recycling processes. Jain et al. highlight that MFA can help identify inefficiencies in material recovery and facilitate better waste management practices (Jain et al., 2017). By understanding the flow of materials throughout the recycling process, shipyards can optimise operations, reduce costs, and enhance the recovery of valuable components. This is particularly crucial in the context of ship recycling, where the economic viability of operations is closely tied to the efficient recovery of materials (Zainol et al., 2023).

Furthermore, the integration of advanced technologies, such as simulation and modelling, can enhance decision-making processes in ship recycling yards, leading to improved operational efficiency and safety (Kurt et al., 2017). Safety considerations are paramount in ship recycling, and the paper underscores the importance of designing ships with safety in mind. The occupational hazards faced by workers in ship recycling yards are well-documented, with exposure to hazardous materials and unsafe working conditions leading to significant health risks (Rahman & Karim, 2015).

By designing ships that minimise the presence of hazardous materials and facilitate safer dismantling practices, the industry can better protect workers and reduce the environmental impact of recycling operations (Zainol, 2023). For example, the use of non-toxic materials and the implementation of ergonomic design principles can significantly enhance worker safety during the dismantling process (Chhetri et al., 2021).

Moreover, the paper highlights the potential for hybrid shipyard concepts that integrate green technologies into traditional recycling processes. Zainol et al. propose that such hybrid models can improve the competitiveness of ship recycling yards by enhancing their environmental performance while maintaining economic viability (Zainol et al., 2023).

The development of eco-friendly ship recycling yards can also foster innovation in recycling technologies, leading to more efficient and effective dismantling processes (Sivaprasad & Nandakumar, 2013).

The papers "Design for Recycle / Engineering Solutions" provides valuable insights into the engineering approaches and design innovations that can enhance the recyclability of ships. By integrating recycling considerations into the design phase, employing tools like Material Flow Analysis, and prioritizing safety, the ship recycling industry can improve its environmental performance and operational efficiency. Future research should continue to explore innovative design strategies and technologies that support sustainable ship recycling practices, ensuring that the industry can meet the challenges of a rapidly changing global landscape.

2.7.5 Social, Law & Policy

This category focuses on social impacts, legal frameworks, and policy implications of ship recycling. Topics may include labour rights, environmental regulations, international treaties (like the Hong Kong Convention), and governmental oversight of the industry.

This critical review synthesises the findings of the paper with relevant literature, highlighting the significance of labour rights, environmental regulations, international treaties such as the Hong

Kong Convention, and governmental oversight in shaping the ship recycling industry. One of the primary concerns addressed in the paper is the social impact of ship recycling, particularly regarding labour rights and working conditions. The ship recycling industry is notorious for its hazardous working environments, especially in developing countries where most recycling activities occur. Gunbeyaz et al. emphasize that more than 90% of global ship recycling capacity is concentrated in countries like India, Bangladesh, and Pakistan, where labour rights are often overlooked (Gunbeyaz et al., 2019).

The lack of adequate occupational health and safety standards poses significant risks to workers, leading to accidents and health issues (Kurt et al., 2017). This situation underscores the urgent need for improved training and regulatory frameworks to protect workers in ship recycling yards (Gunbeyaz et al., 2019). The paper could benefit from a more in-depth exploration of specific labour rights issues and the effectiveness of existing regulations in safeguarding workers. The legal frameworks governing ship recycling are also a critical focus of the paper. The Hong Kong International Convention (HKC), established by the International Maritime Organisation (IMO), aims to ensure that ship recycling is conducted in a safe and environmentally sound manner (Hossain, 2024).

However, the paper highlights the uneven distribution of compliance costs among stakeholders, including nations, shipowners, and recycling yards (Yujuico, 2014). This disparity can lead to non-compliance in countries with weaker regulatory frameworks, exacerbating environmental and social issues. The literature suggests that while the HKC represents a significant step forward, its implementation remains a challenge due to varying national capacities and political will (Hossain, 2024; "A Critical Analysis of Legal Regime of Ship-Breaking and Ship-Recycling in Bangladesh", 2024). Future research should investigate the effectiveness of the HKC in practice and explore potential mechanisms for enhancing compliance among member states. Environmental regulations are another critical aspect discussed in the paper.

The ship recycling process generates significant amounts of hazardous waste, including heavy metals, asbestos, and other toxic materials (Du et al., 2018). The paper emphasizes the importance of robust environmental regulations to mitigate these risks. Du et al. argue that effective waste management practices are essential for sustainable ship recycling (Du et al., 2018). The literature indicates that countries with stringent environmental regulations tend to have better outcomes in terms of waste management and worker safety (Sunaryo & Aidane, 2022).

However, the implementation of such regulations often faces resistance from industry stakeholders concerned about increased operational costs (Gunbeyaz et al., 2020). This tension highlights the need for balanced policies that promote environmental sustainability while ensuring the economic viability of recycling operations. The paper also touches on the role of governmental oversight in the ship recycling industry. Effective oversight is crucial for enforcing compliance with labour and environmental regulations. Hossain notes that increased regulatory scrutiny at both national and international levels has emerged in response to the growing demand for ship recycling (Hossain, 2024).

However, the effectiveness of governmental oversight varies significantly across countries, with some nations lacking the capacity to enforce regulations effectively (Hossain, 2023). This inconsistency can lead to a "race to the bottom," where shipowners opt for recycling facilities in countries with lax regulations, undermining global efforts to improve safety and environmental standards (Mathew, 2021).

Future research should focus on identifying best practices for governmental oversight and exploring collaborative approaches to enhance regulatory compliance across jurisdictions. In conclusion, the paper "Social, Law & Policy" provides valuable insights into the social impacts, legal frameworks, and policy implications of ship recycling. It effectively highlights the challenges related to labour rights, environmental regulations, and governmental oversight. However, further exploration of specific labour rights issues, the practical implementation of the HKC, and best practices for regulatory compliance could enhance the overall analysis. The synthesis of literature reinforces the need for a comprehensive approach to ship recycling that prioritizes social equity, environmental sustainability, and effective governance.

2.7.6 HSE (Health, Safety, and Environment)

The category of "HSE (Health, Safety, and Environment)" provides a comprehensive examination of health, safety, and environmental issues within ship recycling yards. It addresses critical topics such as hazardous material handling, occupational health and safety, pollution control, and strategies to mitigate environmental and human health risks. This critical review synthesises the findings of the paper with relevant literature, highlighting the importance of addressing these issues to improve the sustainability and safety of ship recycling practices. One of the primary concerns raised in the paper is the handling of hazardous materials in ship recycling yards. Nøst et al. conducted a study that revealed high concentrations of organic contaminants in the air surrounding shipbreaking activities in Chittagong, Bangladesh, indicating significant exposure risks for workers and nearby communities (Nøst et al., 2015).

This finding underscores the urgent need for effective hazardous material management practices in ship recycling operations. The presence of persistent organic pollutants (POPs) and other toxic substances not only poses health risks to workers but also contributes to broader environmental degradation (Nøst et al., 2015). The literature emphasizes that without stringent controls and proper training, workers are likely to be exposed to hazardous materials, leading to long-term health consequences (Gunbeyaz et al., 2019). Occupational health and safety (OHS) is another critical area addressed in the paper.

Kurt et al. highlight the challenges associated with measuring occupational noise exposure in ship recycling yards, where safety concerns often limit direct interaction with workers during assessments (Kurt et al., 2017). This limitation complicates the ability to accurately gauge exposure levels and implement effective noise control measures. The lack of comprehensive OHS training and awareness among workers further exacerbates the risks they face (Gunbeyaz et al., 2019). Gunbeyaz et al. emphasize that despite the International Labour Organisation's (ILO) guidelines advocating for worker training, many ship recycling yards, particularly in developing countries, fail to meet minimum safety standards (Gunbeyaz et al., 2019). This gap highlights the need for enhanced training programs and regulatory enforcement to protect workers in the industry.

Pollution control is a significant concern in ship recycling, as the dismantling process generates substantial waste and emissions. Du et al. note that ship recycling yards often struggle with managing hazardous waste, leading to environmental contamination (Du et al., 2018). The paper emphasizes the importance of implementing effective pollution control measures to mitigate the adverse effects of shipbreaking activities on local ecosystems. The International Maritime Organisation (IMO) has issued various regulations aimed at reducing pollution from shipping activities, including the MARPOL conventions, which address oil spills, chemical discharges, and waste management. However, the effectiveness of these regulations often hinges on the capacity of national governments to enforce compliance (Lin et al., 2022). The literature suggests that collaborative efforts between governments, industry stakeholders, and international organisations are essential for improving pollution control in ship recycling operations (Lin et al., 2022). Strategies to mitigate environmental and human health risks are crucial for the sustainable development of the ship recycling industry. The paper discusses various approaches, including the adoption of cleaner technologies and best practices in waste management.

For instance, the development of eco-friendly ship recycling facilities can significantly reduce the environmental footprint of shipbreaking activities (Sunaryo & Aidane, 2022). Zainol et al. propose that hybrid shipyard concepts, which integrate green technologies into traditional recycling processes, can enhance the competitiveness of ship recycling yards while improving their environmental performance (Zainol et al., 2023).

Additionally, studies that focus on the HSE risk in ship recycling are minimal. Risk assessment studies require details and extensive data from the previous accident, which is not recorded correctly by the yards. Hence, the researchers found it difficult to conduct the assessment. Existing risk and hazard studies in ship recycling are summarised in Table below.

Table 2. 3: Risk and hazard studies in ship recycling
(modified from MSC 72/16, UNDP 1990, and Lind 1996)

Title	**Year**	**Author(s)**	**Aim(s)**	**Main Outcome(s)**
A risk assessment tool for the ship recycling industry	2015	R. E. Kurt, S. A. McKenna, S. A. Gunbeyaz, K. G. Rogge, O. Turan1 & I. H. Helvacıoğlu.	To design the methods to fulfil the regulation and to do proper hazard identification and risk management	3 step methods for hazard identification
Review of established risk analysis methods	2006	George Kinigalakis, Mats Karling	To create a tailored risk approach suitable for use in	Systematic review of 28 established risk analysis methods that can

suitable for application on ship recycling			the ship recycling industry.	be applied on a ship dismantling system for identification and assessment of risk as well as for accident investigation.
A sustainable and preventative risk management model for ship recycling industry	2019	Yucel Ozturkoglu, Yigit Kazancoglu, Yesim Deniz Ozkan-Ozen	To identify the risks in the ship recycling industry through the use of a triple bottom line (TBL) approach, and to construct a risk-based conceptual model that encompasses potential hazards, future scenarios, and risk mitigation strategies from a comprehensive and systematic viewpoint.	The integration of the triple bottom line (TBL) approach and risk management in the ship recycling industry.
Integrated Risk Assessment Framework for Ship Recycling Sector	2013	Anand M. Hiremath, Sachin K. Pandey, Anand B. Salve and Shyam R. Asolekar	The framework was developed using results of "What-if Analysis" and it is represented using hybrid technique	The integrated risk assessment framework developed to aware the workers regarding the

			called “Fault Tree Analysis”.	sources of risks depending upon the type of work activity and working zone in the ship recycling yard
Development and validation of three-step risk assessment method of ship recycling sector	2015	Karin Garmer, Hasse Sjostrom, Anand Hiremath, Atit K. Tilwankar, George Kini galakis, Shyam R Asolekar	To validate the 3 step method framework	The three-step method give consistent result in a variety scenario of validation

The initial study was carried out in 2006 as part of the SHIPDISMANTL project, which was the first European Union-funded initiative specifically focused on ship recycling. The project was funded with 1.5 million euros through the 6th European Research Framework Programme (FP6, 2005-2009) and aimed to perform a comprehensive evaluation of existing risk assessment tools suitable for the ship recycling process with the objective of creating a tailored approach that can be applied in the ship recycling industry. The output shows that one of the essential criteria for selecting a suitable risk analysis method is simplicity, as ship recycling systems are usually very complicated. Also, systematic risk analysis can be applied to a ship dismantling system to identify and assess risks and accident investigations. (Kinigalakis, 2006)

An integrated risk assessment methodology for the ship recycling industry was developed in 2013. The 'what-If' method and Fault Tree Analysis were combined to allow workers to understand the sources of risks based on the type of work activity and location within the ship recycling yard. It was proposed that the risks in a ship recycling yard vary by location, not being uniform throughout the yard, and therefore the work activities were divided into three zones for a clearer understanding of the ship recycling process: Inside the ship, intertidal, and primary/secondary zone (Hiremath, 2013)

Furthermore, the 3-step method, a comprehensive and user-friendly hazard identification approach, was also created for ship recycling (Kurt, 2015). In addition, the research mentioned that the strategy used should engage end-users, which is critical for facilitating the implementation and acceptance of needed health and safety measures. Moreover, the validation of the 3-step method shows that the method gives consistent results in a variety of scenarios of validation (Garmer, 2015)

As shown in the figure 2.17, the three-step method came up with a structured and guided framework through two distinct sections; a base for ship recycling and a safe ship recycling plan. The first step of the Three-Step Method assures that the fundamental standards established by national and international agencies for Ship Recycling operations are met.

Furthermore, the second step is identifying the risk assessment scope and dangerous job. Then, the group of experts selects the first hazardous job task and inputs it into the screening tool (Document D). The screening tool allows the group to identify and assess all potential hazards in the job task "Hazards for Hazards Screening" (Document E).

At last, a third step involves carrying forward the hazards based on the group's judgment to the 'Deeper Risk Assessment Sheet' (Document F). During this section, the group must discuss and document more details about the hazard. Using information related to casual risk factors, location, potential effects, severity (S), and probability (P) in the group's assessment of the hazard, they then calculate a level of risk (R).

Hence, a three-step method provides a list of hazardous tasks; the checklist should be more detailed than the list of hazards, and its causal factor needs to be upgraded. Besides, the tree step methods only present the dangerous thing that needs to be prioritized to be taken into risk precaution step; it does not provide a further risk estimation that needs to be calculated to understand the potential loss caused by the hazards.

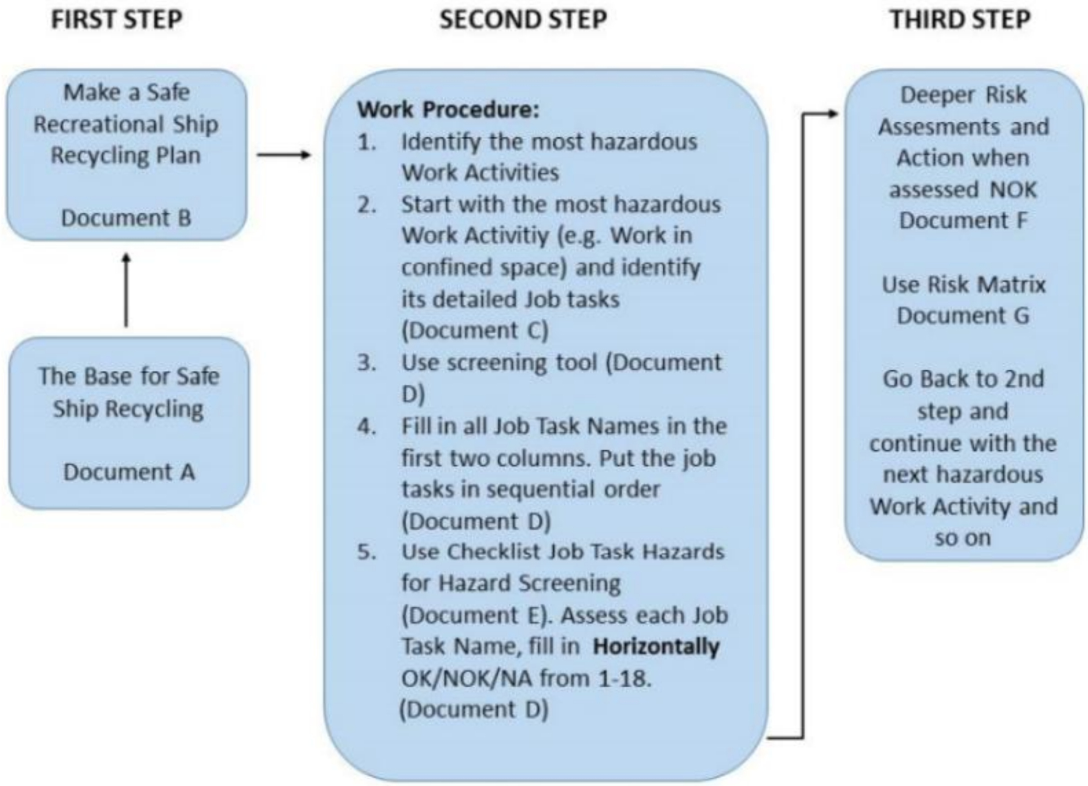


Figure 2.17: The three step methods (Kurt, 2015)

The latest research related to the risk in the ship recycling process was done in 2019. By applying TBL (Triple Bottom Line) to the ship recycling industry (Figure 2.18), this research seeks to define risks about the industry and propose preventative measures by using a holistic approach and system approach for a holistic view of the issue. In this study, Fuzzy DEMATEL is used to solve complex problems by providing causal relationships and order of importance for factors. (Ozturkoglu, 2019)

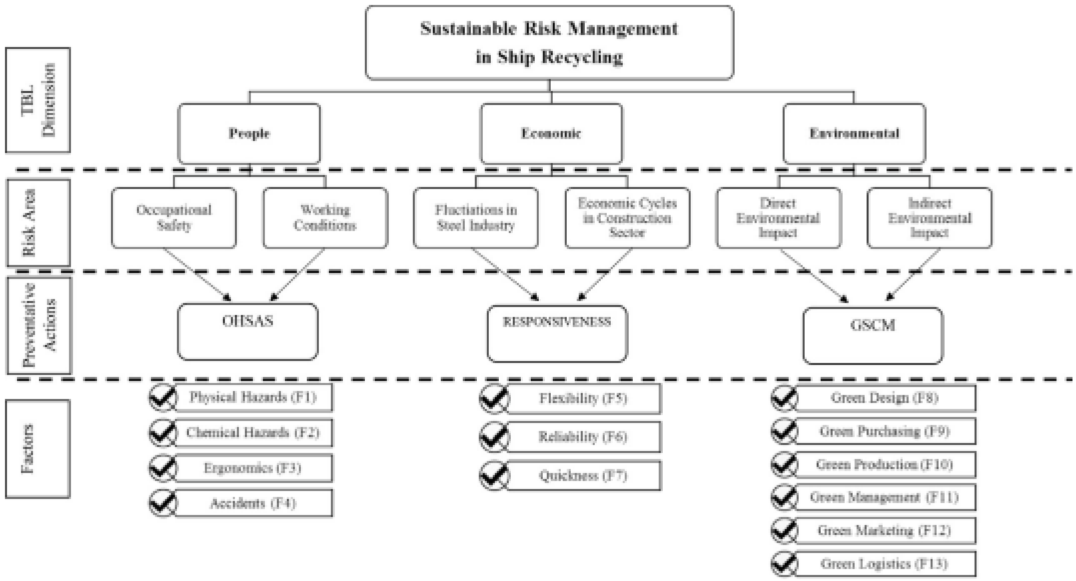


Figure 2.18: TBL-Based conceptual risk model for ship recycling (Ozturkoglu, 2019)

To conclude, "HSE (Health, Safety, and Environment)" research provides valuable insights into the health, safety, and environmental issues within ship recycling yards. It effectively highlights the challenges associated with hazardous material handling, occupational health and safety, pollution control, and risk mitigation strategies. However, further exploration of specific case studies and the effectiveness of implemented strategies could enhance the overall analysis. The synthesis of literature reinforces the need for a comprehensive approach to ship recycling that prioritizes worker safety, environmental sustainability, and regulatory compliance.

2.7.7 General Topics

Generic research within the ship recycling sector provides broad overviews and introductory insights that lay the foundation for more specialised studies. These studies often cover a wide range of issues associated with ship recycling, from worker health risks to environmental contamination, without focusing exclusively on a single aspect. This category of research serves as a valuable resource for understanding the multifaceted nature of ship recycling, yet its breadth can sometimes limit the depth of insight in any specific area.

Several studies (e.g., Chang, Wang, & Durak, 2010; Salim, 2009) provide foundational information on the overall hazards associated with ship recycling. This includes exposure to asbestos and other hazardous materials, which is particularly concerning due to the long latency period of related illnesses, such as cancer (Courtice et al., 2011). These studies have identified various toxic materials commonly found in the ship dismantling process, such as asbestos, heavy metals, hydrocarbons, and plastics, that pose significant health and environmental risks (Tilwankar et al., 2008). Such research offers valuable insight into the cumulative risk exposure faced by workers and surrounding communities, while also highlighting the broader environmental impact of ship recycling operations on coastal and marine ecosystems.

Despite the importance of these findings, generic studies in this field often face limitations in terms of specificity and actionable outcomes. While they identify the presence of hazardous materials and environmental pollutants, there is frequently a lack of detailed data on exposure levels, toxicity thresholds, and the long-term effects of these substances on human health and ecosystems. Furthermore, these studies seldom provide insights into region-specific conditions, overlooking variations in environmental and regulatory contexts that may affect the types and degrees of hazards encountered. Consequently, while generic research establishes the scope of issues within ship recycling, it tends to fall short in offering targeted recommendations for mitigation.

One area where generic research could be enhanced is in the quantification and categorization of hazards by specific regions or yard types. Regional studies that incorporate contextual factors such as local climate, waste management infrastructure, and worker safety protocols could provide a more nuanced understanding of how ship recycling impacts health and the environment. Additionally, integrating real-time monitoring data, such as emissions tracking and air quality assessments, could help establish clearer benchmarks for acceptable levels of exposure, thereby facilitating more precise regulatory recommendations. However, while generic research plays an essential role in building foundational knowledge about ship recycling, its broad focus limits the specificity of its findings. Future studies should seek to address these limitations by including more detailed analyses of exposure levels, context-specific variations, and quantifiable environmental impacts. By doing so, generic research can evolve to offer actionable insights that bridge the gap between broad knowledge and specific, implementable solutions in the ship recycling sector.

Moreover, while the preceding review of academic research has primarily focused on operational, economic, and regulatory aspects of ship recycling, recent global trends are shifting the industry towards a more sustainable and holistic approach. The traditional focus on material recovery and regulatory compliance is no longer sufficient to address the complex environmental, social, and economic challenges associated with ship recycling. In response, circular economy principles have emerged as a key paradigm, promoting not only the recycling of ships at the end of their life but also designing vessels for easier dismantling, minimising hazardous waste, and creating closed-loop value chains that extend beyond the shipyard.

This shift is reinforced by the entry into force of the Hong Kong Convention in 2025, the European Union's Green Deal objectives, and global sustainability commitments such as the United Nations Sustainable Development Goals (SDGs). Integrating circular economy concepts into ship recycling research provides a forward-looking framework for innovation, policy development, and industry best practices. The next section explores how these principles are being applied to ship recycling and highlights recent developments that bridge the gap between academic research and practical sustainability goals.

2.8 Recent development and future direction

The entry into force of the Hong Kong Convention (HKC) on 26 June 2025 represents a transformative milestone for the global ship recycling industry. For the first time, ship recycling practices are governed by a unified, mandatory international framework, requiring signatory countries to implement strict standards for worker safety, hazardous material management, and environmental protection (IMO, 2025a; Lloyd's Register, 2025). The ratification of key ship recycling nations such as India, Bangladesh, and Turkey was instrumental in reaching the thresholds for global tonnage and recycling capacity, underscoring their pivotal roles in shaping the future of ship recycling (IMO, 2025b; Bureau Veritas, 2025).

This regulatory shift addresses long-standing concerns over inconsistent practices and inadequate safeguards, particularly in South Asian countries where beaching remains the dominant method (NGO Shipbreaking Platform, 2022; Ahamad et al., 2021). With the HKC now fully in effect, the industry focus is shifting from voluntary guidelines to enforceable standards. This transition has triggered broader conversations around sustainability and circular economy (CE) approaches, reframing ship recycling as part of a resource-efficient system rather than merely a waste disposal activity. CE models promote maximising material recovery, reducing waste generation, and creating closed-loop value chains, aligning ship recycling with global sustainability objectives (Tola et al., 2023; ElMenshawy et al., 2024).

For example, approximately 96% of a ship's weight can be reused or recycled, offering significant opportunities for resource conservation when processes are managed effectively (OECD, 2019). Steuer et al. (2021) highlight the potential for shipyards to transition from traditional recycling to refurbishment and repair operations, extending vessel lifespans and reducing the demand for resource-intensive new builds. Furthermore, CE principles encourage design for disassembly, where vessels are built using modular structures and non-toxic materials to simplify dismantling and reduce hazardous waste generation (Favi et al., 2019).

The HKC requirement for vessels to maintain an Inventory of Hazardous Materials (IHM) throughout their operational lifecycle enhances transparency and supports the traceability of recyclable and hazardous components (IMO, 2019). This creates a foundation for digital tracking systems and data-driven compliance monitoring, fostering more efficient and sustainable operations. These advancements complement European Union regulations, which already mandate certified recycling facilities and stringent material handling processes (Moncayo, 2016; European Commission, 2016).

Technological innovation will play a decisive role in the industry's transformation. Digital twin (DT) technologies and advanced simulation tools are increasingly recognised for their potential to enhance real-time monitoring, predictive risk assessment, and optimised decision-making within ship recycling yards (Zio & Miqueles, 2024; VanDerHorn et al., 2022). DTs allow for virtual representations of ships, linking design data to end-of-life dismantling processes, enabling precise planning and material recovery optimisation. These technologies align with broader maritime trends in smart shipping, automation, and decarbonisation, positioning ship recycling yards as integral components of a data-driven maritime ecosystem (DNV, 2025).

At the industry level, several stakeholders are moving towards CE-aligned practices. For instance, shipping companies such as NYK Group have adopted corporate ship recycling policies that align with environmental, social, and governance (ESG) principles, ensuring vessels are dismantled only at certified, sustainable facilities (Bureau Veritas, 2025). Moreover, research highlights the importance of stakeholder collaboration and multi-criteria decision-making to balance economic, environmental, and social factors during recycling operations (Mathew, 2021; Sunaryo & Aidane, 2022).

Despite these advancements, significant challenges remain. Developing nations currently handle nearly 70% of global ship recycling capacity through beaching methods (NGO Shipbreaking Platform, 2022). Upgrading infrastructure to comply with HKC standards will require substantial financial investment, technical expertise, and policy alignment. Without coordinated international efforts, there is a risk of regulatory dumping, where non-compliant vessels are diverted to less-regulated facilities (Rahman et al., 2021).

The next decade will be critical in determining whether the ship recycling sector can successfully transition from low-cost, high-risk operations to sustainable, competitive systems that support both economic development and environmental protection. Through integrating risk-based cost-benefit assessments with these emerging regulatory and technological frameworks, this study seeks to support decision-making processes that enhance worker safety, operational efficiency, and long-term sustainability in global ship recycling.

The concept of the circular economy (CE) reframes ship recycling not merely as waste disposal, but as a strategic system for resource retention through eco-design, reuse, and closed-loop recovery. This shift is critical in transforming ship recycling from a hazardous, linear process into a value-generating and environmentally responsible industry. Tola et al. (2023) conducted a systematic review highlighting how CE frameworks can be integrated into ship recycling by linking life-cycle management with reuse flows, coupling demolition with green market development, and promoting regulatory strategies that Favor reuse and disassembly.

Similarly, ElMenshawy et al. (2024) propose that CE principles can support sustainable development by creating circular supply chains, emphasizing long-term social and environmental gains. In engineering practices, Okumus et al. (2024) developed circularity metrics for maritime systems, offering a structured pathway for assessing and improving the sustainability of recycling operations. Digitalisation further enables CE adoption. Madusanka et al. (2023) reviewed the progression of digital twins in the maritime domain, suggesting how virtual modelling can support eco-design and lifecycle tracking. Broadening this, Mauro et al. (2023) conducted a critical review, identifying gaps and potentials in applying digital twin technology to various maritime operations.

Applications extend beyond design, Homayouni et al. (2025) demonstrated how DTs can enhance seaport sustainability through real-time optimization, a model also adaptable to ship-recycling yards. Deploying CE in ship recycling also aligns with green certification efforts among industry stakeholders. For instance, the NYK Group implemented a CE-aligned ship recycling policy, adding a verified yard in Bangladesh to its certified list under ESG criteria

Through integrating CE principles, digital twin technologies, and stakeholder certification frameworks, ship recycling can move towards a model that supports material recoverability, risk reduction, and sustainable operations. These developments provide a forward-looking foundation for evaluating how risk-based cost-benefit frameworks, like the one developed in this thesis, can support sustainable transitions in global ship recycling.

The previous sections have outlined the evolution of ship recycling regulations, emerging sustainability paradigms such as circular economy principles, and the role of digitalisation in transforming operational practices. While these developments highlight promising pathways for improvement, the literature also reveals persistent gaps that prevent the industry from achieving holistic safety, environmental, and efficiency objectives. For instance, fragmented regulatory enforcement, limited adoption of advanced technologies, and the absence of integrated cost–risk–productivity frameworks continue to constrain progress. These limitations underscore the need for a unified approach that brings together risk assessment, sustainability considerations, and operational efficiency within a single decision-support framework. The next section therefore synthesises the identified gaps and proposes an integrated perspective to guide future research and practical implementation in ship recycling.

2.9 Towards an Integrated Approach in Ship Recycling

The complex nature of ship recycling requires an integrated approach that addresses various challenges across environmental, safety, policy, and efficiency dimensions. Existing studies reveal several cross-cutting gaps that hinder the industry's progress toward sustainable practices. This section identifies these overarching gaps and presents a proposed integrated framework aimed at enhancing safety, environmental protection, and operational efficiency in the ship recycling sector.

2.9.1 Identified Research Gaps and Challenges

The review of various studies on ship recycling reveals several significant gaps across categories that hinder the advancement of the industry towards more sustainable and safe practices.

2.9.1.1 Inconsistent Data Collection

A notable gap is the inconsistency in data collection methods across different studies. For instance, while some studies utilise Material Flow Analysis (MFA) to assess material recovery rates, others rely on anecdotal evidence or aggregate data without detailed ship-by-ship assessments Jain et al. (2016). This inconsistency complicates the ability to draw comprehensive conclusions about the efficiency and environmental impact of ship recycling practices globally.

2.9.1.2 Lack of Standardised Framework to Assess HSE risks

There is a clear absence of standardised frameworks for assessing health, safety, and environmental (HSE) risks in ship recycling yards. While various studies highlight the importance of occupational health and safety, the lack of a unified approach to risk assessment and management leads to varied practices and outcomes across different regions (Gunbeyaz et al., 2019). This inconsistency can result in significant health risks for workers and environmental degradation.

2.9.1.3 Process Efficiency and Improvement Focused Solely on Productivity

A considerable number of studies aim to improve the efficiency and productivity of ship recycling operations. However, these efforts often prioritise operational gains while overlooking critical health, safety, and environmental (HSE) factors. For example, models developed to optimise dismantling activities or maximise material recovery tend to focus on achieving faster and higher output, with limited attention to the potential risks to workers or the environmental consequences of intensified processes (OECD, 2019). This highlights the need for integrated approaches that balance productivity with robust safety and environmental safeguards

2.9.1.4 Limited International Policy Alignment

The review indicates a lack of alignment among international policies governing ship recycling. Although the Hong Kong Convention establishes guidelines for safe and environmentally sound recycling, its implementation varies widely across countries due to differing national capacities and political will (Hossain, 2024). This misalignment can lead to a "race to the bottom," where shipowners opt for recycling facilities in countries with lack regulations, undermining global efforts to improve safety and environmental standards.

2.9.2 Proposed Integrated Framework

To address these gaps, this PhD research proposed integrated framework should encompass a multi-disciplinary, multi-stakeholder approach that incorporates insights from all research areas related to ship recycling. This framework should include:

- Multi criteria and multi expertise decision support is integrated into decision making: From risk identification to quantification, the process requires input from multiple experts. This integration can be achieved through collaborative framework that bring together stakeholders from government, industry, academia, and civil society to share knowledge, best practices, and innovations in ship recycling.
- Standardised Assessment Tools: The development of standardised assessment tools for HSE risks, process flow, and economic viability should be included to support ship recycling yard implementation in decision support. These tools can facilitate consistent data collection and analysis, enabling stakeholders to make informed decisions based on reliable metrics.
- Utilisation of Simulation Approaches: In order to create the confidence among SR owner to make improvements, they need to provide with simulation tools to ensure that they will get benefit on it in addition of complying, this tool has not been developing especially the one integrate HSE risk. Therefore, there is a risk-based approach needed for decision making for ship recycling yard design and improvement and cost benefit of this improvement should be properly estimated and considered.

2.10 Chapter Summary

This chapter has presented the ship recycling industry's overall picture and the current challenges, issues, and opportunities. Moreover, studies on the risk and simulation applications were discussed, and the studies that can be useful in this thesis are summarised.

Chapter 3. Research Question, Aim, Objectives and the Gap

3.1 Chapter Overview

This chapter represents the identified gap and defines the research question, aims, and objectives addressed in this thesis.

3.2 Research Question

In the ship recycling industry, the implementation of strategies aimed at mitigating hazards and increasing productivity can sometimes be viewed as being in contrast to each other, which implies that the goals or methods of these two approaches might seem conflicting or incompatible at times, rather than working together in harmony. This is because some hazard risk mitigation measures may lead to decreased productivity and efficiency, and conversely, some productivity-enhancing measures may lead to an increased risk of hazards. Therefore, there is a need to develop a framework to systematically design green ship recycling yards to improve the health, safety, and environment (HSE) while benefiting productivity and increasing operational efficiency. In this way, new ship recycling yards, which have higher investment requirements and operating costs than the subnormal yards, can be designed.

Therefore, the research question that the author aims to answer in this Ph.D. study is;

"Can HSE (Health, Safety and Environment) related risks and risk control measures in a ship recycling yard be handled in an integrated framework that allows cost-benefit assessment?"

3.3 Aim and Objectives

This research aims to design a framework to help quantify risk and benefit for different technologies and procedures in ship recycling, allowing decision-makers to make evidence-based decisions while improving ship recycling facilities. This aim will be achieved by fulfilling the specific objectives.

1. To conduct a thorough investigation of the hazards associated with ship recycling activities.

2. To undertake a comprehensive analysis of Health, Safety, and Environment (HSE) risks, incorporating meticulous data collection and extensive field studies.
3. To design and develop observation and field studies to collect missing process performance data from ship recycling yard.
4. To develop a robust risk assessment framework that aligns specifically with the intricacies of a ship recycling yard.
5. To identify suitable risk control measures, while concurrently evaluating associated costs.
6. To perform a discrete-event simulation with the aim of Optimising productivity and cost in the ship recycling context.
7. To validate the proposed framework through an empirical case study, with a specific focus on Indonesia's ship recycling sector.
8. To acquire a detailed understanding of the Indonesian context, particularly its potential to bolster growth and development in the ship recycling industry.

3.4 Importance of Conducting this Study

In order to achieve safe & environmentally sound practices in ship recycling yards, decision-makers should have a systematic way to capture hazards and risks during ship recycling activities. As mentioned before, due to the health, safety, and environmental problems caused by the industry, much more stringent regulations came into force that will impact the procedure and operations cost. International regulators such IMO published ship recycling regulations to improve ship recycling activities regarding safety and environmental protection, which is not fully adopted and implemented by decision-makers, especially in developing countries. There is currently a lack of research that can provide scientific evidence to quantify and justify the effectiveness of improvements in ship recycling facilities so that the developments can be evaluated in a risk-based manner.

However, the risk reduction alone is not enough, the impact of the new risk control measure on the current operation cost should also be considered in a transparent framework. Ship recycling process involves many serious risks and most of the time, lack of safety assessment and proper planning. Dismantling ships require complex procedures, and many risks involved in the process, therefore, there is a need for a structured and guided way of conducting assessment for each job task. In addition, incorporating hazard identification and risk management in ship recycling yards, a number of experts from different backgrounds is needed. The current health and safety risk assessment framework in ship recycling fails to address the additional impacts or benefits of risk control in terms of productivity in an integrated framework.

Therefore, the development of an integrated risk and productivity framework will provide a tool for the decision-makers to estimate the cost-benefit for the application of risk control with regards to human life, environmental protection, and increment of productivity, which will show the most cost-effective risk control options to be identified and implemented to decrease the risk in ship recycling process. Implementing new procedures or technology at the ship recycling facilities will consider risks through a safety assessment framework. This research will develop a risk-based framework to address the identified gap which will be achieved by employing discrete event simulations to estimate and quantify the impact in a cost-benefit assessment. This new framework will provide confidence to investors to make improvement decisions.

3.5 Bias Mitigation

To ensure the credibility and validity of the research findings, potential sources of bias were carefully considered and mitigated throughout the study. Researcher bias was reduced by maintaining a clear audit trail of all decisions, documenting assumptions, and using consistent data collection procedures. Expert and selection bias were minimised by recruiting a diverse panel of experts from different backgrounds, including local and international stakeholders, using transparent selection criteria. Cultural and contextual bias were addressed by incorporating perspectives from multiple countries and ensuring that questions were framed in a culturally sensitive and neutral manner. These steps improve transparency and reproducibility, supporting robust, evidence-based recommendations.

3.6 Chapter Summary

This chapter has summarised the research question, research aim, research objectives, and research gap of this research study.

Chapter 4. Approach Adopted

4.1 Chapter Overview

This chapter briefly defines the selected approach to achieve the aims and objectives of this PhD research study. The approach adopted in this study consists of the following steps: a literature review, analysis of the current situation in ship recycling process related to risk through field observation, design of discrete event simulation for productivity analysis, development of structured risk assessment methods using multiple attributive group decision making, creation of an integrated framework considering productivity, health, safety, and environmental risks in ship recycling process with discrete event simulation, structured risk assessment methods, and cost-benefit assessment, demonstration of the framework on an Indonesian Ship recycling Yard, and comparison of the model results with the current situation in ship recycling process. Each phase is further explained in the subsequent sections.

4.2 Mind Map of Approach Adopted

In Chapter 2, a concise overview was provided on various ship recycling topics. This review brought to light the inadequate attention given to the critical matter of mitigating risks in ship recycling industries, particularly in terms of maximizing productivity benefits. As a result, this thesis focuses on addressing this specific issue. In order to address the identified gap and achieve this study's defined aims and objectives, it was essential to establish a clear and simple strategy.

The combination of risk and productivity-related was not integrated into yard development and improvement frameworks in the ship recycling processes. In the absence of an integrated framework in studying the productivity benefit in terms of risk control options, this PhD study adopts an approach demonstrated in the diagram shown in the Figure 4.1 below.

Figure 4. 1: 3 Phase Approach Adopted by this Research

4.2.1 Investigation and comparative assessment of safety and simulation approach

Before starting the development of the framework, it was essential to conduct a comprehensive investigation of the academic approaches to the ship recycling industry. The outcomes of this investigation, summarised in Chapter 2, showed that while some research has linked risk assessment to operational planning, such as the work by Hiremath et al. (2016) who developed ship-specific recycling plans integrating risk identification with HSE controls, while they have addressed risk assessment and planning for ship recycling, there remains no integrated study that combines risk, cost-benefit analysis, and productivity modelling. This research addresses that gap by linking risk control measures with discrete-event simulation and economic evaluation. Therefore, research conducted in similar industries (shipbuilding and other dismantling/recycling industries) was reviewed to identify relevant approaches and adapt them to ship recycling with all the essential factors. To develop this integrated framework, discrete-event simulation and risk assessment methods will be studied in detail to determine the most suitable tools for modelling and improving ship recycling operations.

Hazard identification and risk analysis methods for ship recycling operations will be reviewed, and the practical approaches to ship recycling will be utilised in the framework development. Due to the specific characteristics of the ship recycling process, there is a need for a particular approach to identifying hazards and calculating risks. In order to develop a suitable approach, the existing problems in tackling hazards and risks, as well as the requirements needed for identifying the involved hazards, will be investigated. In terms of benefits, the previous research on ship recycling discrete-event simulation will be expanded and thoroughly examined to determine the efficiency gain achieved through risk control. This analysis aims to identify additional gains beyond the potential preservation of human life.

Furthermore, to design a framework which facilitates risk-based improvement decisions in the ship recycling process, the study will involve an investigation of existing studies focusing on various ship recycling processes, particularly with regard to risks and efficiency. The findings from these studies will be utilised to develop methods that will be seamlessly integrated into the framework of this research.

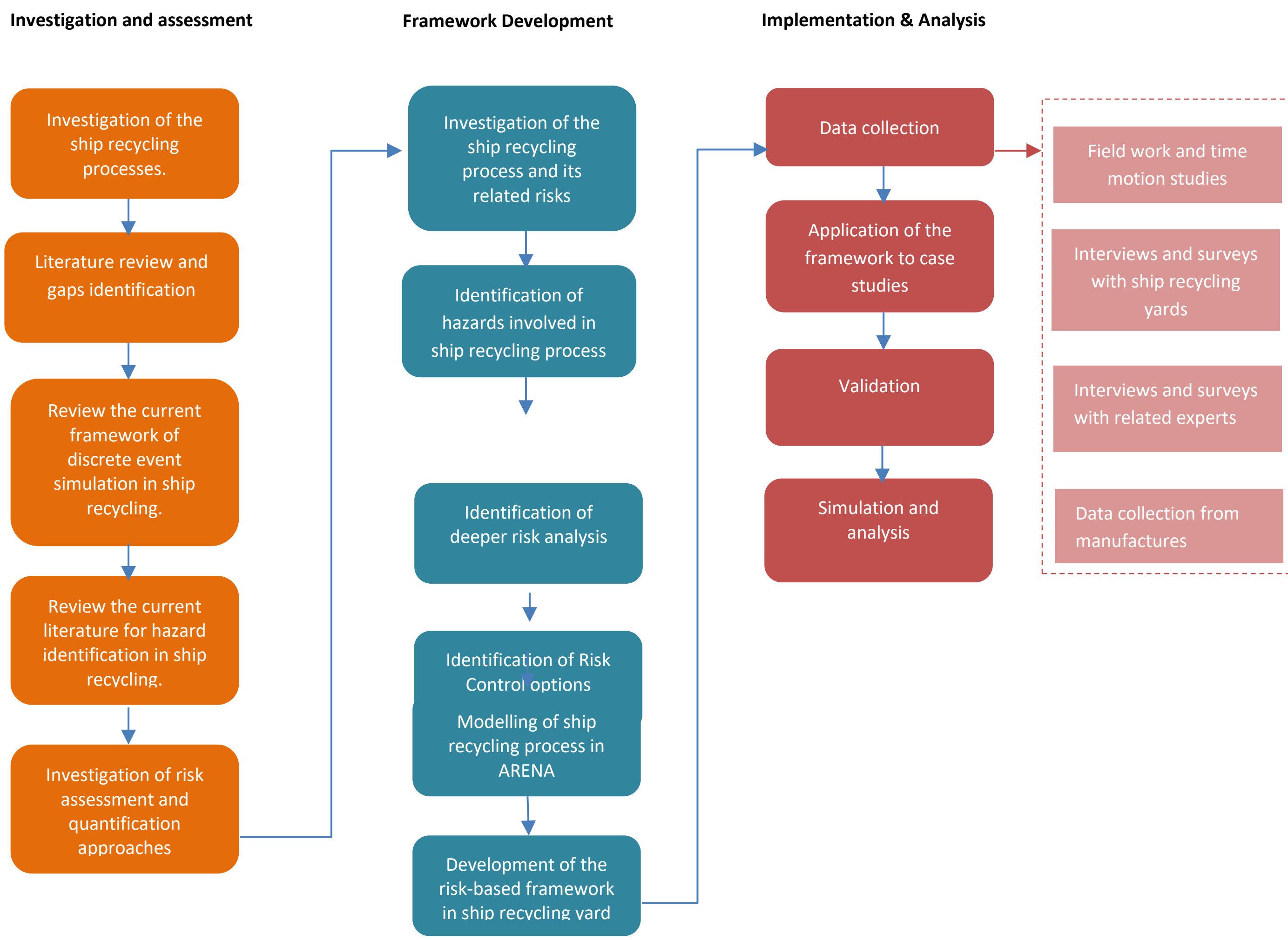


Figure 4. 2: Framework and phases of this thesis.

4.2.2 Framework Development

- **<u>Investigation of ship recycling process and its related risks</u>**

  This PhD thesis aims to create a sophisticated simulation framework, underpinned by actual process models and reliable process data. The precision of these simulations and the trustworthiness of their outcomes hinge significantly on the efficacy of data collection and processing. As such, the imperative nature of field investigations and data-gathering activities within the scope of this thesis cannot be overstated.

  Initially, through the course of observational studies, the researchers meticulously recorded comprehensive step-by-step operations carried out within a ship dismantling yard.

Following this, they identified risks and their respective causations within each ship recycling process. To supplement the data, expert consultations were conducted in the form of structured surveys, interviews, and workshops. These consultations provided valuable insights into cost details and other relevant information that was otherwise inaccessible during field investigations.

- **Hazard identification**

  Hazard identification aims to curate a tailored list of potential hazards and associated scenarios, ranked according to their risk level, specific to the problem at hand. The objective of this project is to pinpoint structured hazard identification techniques, explicitly devised for ship recycling. This involves compiling a roster of potential threats that could precipitate an accident and evaluating various hazards through a fusion of available data and expert insight. Central to this approach is the requirement for a structured group to scrutinize the hazard identification process, determining the origins and impacts of a potential accident, as well as any correlated hazards. This team, responsible for conducting such methodical evaluations, should comprise experts from diverse fields to aid in the identification of hazards. Consequently, this structured and supervised approach to tasks integrates both risk identification and management.

- **Risk analysis**

  The goal of the risk analysis phase is to delve deeper into the origins, triggering events, and consequences of the most severe accident scenarios unearthed during the hazard identification process. This can be achieved using suitable risk modelling tools, which subsequently allow us to concentrate on high-risk locations and discern the factors that influence the degree of risk in these areas. In order to address the present circumstances effectively, it's crucial to manage various types of risk, including those posing threats to individuals, the environment, or property, in the most suitable manner.

- **Risk control options**

  The necessity lies in pinpointing risk control measures and subsequently consolidating them into a manageable number of Risk Control Options (RCOs) that serve as viable regulatory alternatives. This process is executed in four key stages:

  - Identifying areas of risk that necessitate control,
  - Discovering potential risk mitigation strategies,

- Assessing the effectiveness of the Risk Control Measures (RCMs) in reducing risks through a re-evaluation of risk analysis, and
- Merging RCMs into logical regulatory choices.

The objective of this phase is to devise risk control alternatives that tackle both existing and newly emerged risks brought about by novel technologies or innovative operational and management methodologies. An extensive array of mitigation strategies should be considered, encompassing both historical hazards and newly identified risks (as a result of stages 1 and 2), culminating in a multitude of risk management measures. The application of techniques designed to address both specific risks and potential issues should be promoted.

- **Productivity measurement through discrete-event simulation**

Productivity is gauged by the collective efficiency, or integrated efficiency, of all components involved in the manufacturing process, including human resources, machinery, and other devices and equipment, ty of raw material, management, and the overall proficiency of the production system.

In this research, an additional advantage derived from the implementation of risk control options, as mentioned in step 4, will be evaluated using discrete-event simulation through ARENA software. This measure will be quantified as the ratio of average acceptable output per period to the total costs incurred through various resources consumed in that period.

- **Cost-benefit assessment**

The goal of the Cost-Benefit Analysis is to discern and examine the benefits and expenses associated with implementing each Risk Control Option (RCO) identified in the preceding phase. The stages of a cost-benefit analysis are as follows:

  - Utilise the identified risks to establish the base case risk levels of the situation,
  - Arrange the RCOs defined in step 4 to ensure the costs and benefits of adopting an RCO are clearly stated,
  - Compute the costs and benefits of the RCOs to facilitate evidence-based decision-making recommendations.

Furthermore, several indices such as the Gross Cost of Averting a Fatality (Gross CAF) and Net Cost of Averting a Fatality (Net CAF) will be utilised to evaluate cost-effectiveness in relation to preserving human life. Ultimately, this analysis will conclude in recommendations, which should be delivered to the pertinent decision-makers in an auditable and traceable fashion. These recommendations will be founded on the comparison and ranking of all hazards and their root causes, the comparison and ranking of risk control options based on their associated costs and benefits, and the identification of those risk control options that ensure risks are as low as reasonably practicable.

- **Integration of framework component**

  The developed framework integrates three main components, risk assessment, discrete-event simulation (DES), and cost-benefit analysis (CBA) into a single iterative process. This integration ensures that each component informs and validates the others, creating a continuous improvement loop.

  The process begins with hazard identification and risk assessment, which identify the most critical risks and define risk control options (RCOs). These outputs are then used to design the simulation parameters in ARENA, ensuring that the DES model reflects realistic operational and safety conditions within ship recycling yards.

  The simulation model evaluates the operational performance of different RCO scenarios by identifying bottlenecks, resource utilisation, and productivity improvements. These quantitative results are subsequently fed back into the cost-benefit analysis, where both the safety benefits (e.g., reduction of fatalities and injuries) and the operational efficiency gains are evaluated together.

  This iterative relationship between risk assessment, simulation, and cost-benefit evaluation creates a unified decision-making tool. As illustrated in Figure 4.2, the integration ensures that risk control strategies are both effective in improving safety and efficient in enhancing productivity, addressing the dual objectives of safer and more sustainable ship recycling practices.

4.2.3 Implementation and Analysis

Upon completion of the simulation models and the corresponding framework, the capabilities of the developed approach will be showcased via a case study. For the simulation methodology to be successful, it necessitates comprehensive data on operations, process durations, and costs. In addition, the risk component also requires data for a more thorough risk assessment. To amass the missing data, a data collection exercise will be undertaken. A field study will be conducted to gather operational data from a real-world ship recycling yard. This data collection effort will be supplemented with interviews, workshops, and questionnaires involving recycling experts, other stakeholders, and manufacturers of the equipment used in the yard.

4.3 Chapter Summary

This chapter delineates the multifaceted approach used in this PhD research. It encompasses the creation of a detailed simulation framework supported by reliable data, a structured hazard identification process tailored for ship recycling, and an in-depth risk analysis utilising specialised modelling tools. The chapter further explores the development of Risk Control Options (RCOs) to address a spectrum of risks, the measurement of productivity through discrete-event simulation, and a comprehensive cost-benefit assessment to evaluate the viability of each RCO. The final part of the chapter underscores the importance of data collection through field studies and expert consultations, setting the stage for the practical application of the developed framework.

Chapter 5. Integrating Risk-Based Methodologies into Ship Recycling Practices

5.1 Chapter Overview

In Chapter 2, risk assessment has been proposed as an additional method to address the limitations of the existing ship recycling yard facilities. This chapter will introduce a risk-based approach, which has become a widely accepted method in many different areas of study. This approach focuses on identifying and assessing potential risks and using that information to inform decision-making and proactive measures to mitigate or manage those risks. This methodology has been found to be effective in various fields and is therefore being introduced in this chapter. Starting with explaining risk-based approaches, the chapter follows a comparative analysis of each approach in line with the ship recycling case. Furthermore, safety analysis methods applied to the risk-based design are explained starting from the explanation of qualitative and quantitative methods; the number of well-known probability calculations is also discussed in the chapter, along with the benefits and drawbacks of their use for risk-based design. Finally, the limitations of applying the current approach to ship recycling will also be discussed.

5.2 Risk-based Approach in the Maritime Area

The concept of risk relates to the probability of an undesirable event occurring in the future, which might emerge from a situation bearing potential harm or adverse effects. Risks can stem from numerous scenarios including, but not limited to, market instability, disruptions in supply chains, project failures, security breaches, quality and safety errors, environmental concerns, natural disasters, or even intentional attacks to causes harm. Understanding and managing these risks require their proper identification and evaluation. As stated by Hing Kai Chan (2013), these steps are crucial in successful risk management (Hing Kai Chan, 2013).

The ship recycling process is often executed without an adequate understanding of safety. This lack of transparency and reporting of accidents leads to uncertain data concerning risk measures. The process is fraught with significant risks and is often conducted without sufficient preparation. Given the operation's complex nature and inherent risks, it's crucial to structure and direct job responsibilities effectively.

Moreover, it's essential to integrate risk management and hazard identification across various areas of expertise. As such, a dedicated risk assessment approach for the ship recycling process is needed. This approach should utilise a structured risk assessment tool aimed at identifying hazards and assessing the degree of risk, providing prioritization cues for subsequent actions. Furthermore, due to a dearth of quantitative data, this thesis will focus on a hybrid risk analysis approach, blending both qualitative and quantitative methodologies.

5.2.1 Safety Case

The use of safety cases, which justify why a system is allowed to operate within a particular environment, is becoming more prevalent. This approach has deep roots in the United Kingdom, where it's widely employed in safety critical industries, such as the oil and gas sector. Within the realm of offshore technology, safety cases play a pivotal role in offshore installation design. A safety case encapsulates every aspect of a plant's or process's safety, including hazard mitigation strategies. It must provide enough information to convincingly demonstrate that:

- Major hazards capable of leading to severe accidents have been identified.
- Risks have been evaluated, and efforts have been taken to reduce them to the lowest reasonably practicable level (ALARP).

Therefore, a safety case should be created not only to demonstrate safety by design but also to clarify operational requirements, ensure ongoing safety assurance through regular reviews, and detail emergency response protocols. It's crucial to outline a selection of serious accident scenarios, examine their potential consequences, and compute the probability of their occurrence. For more effective prediction and control of safety incidents, it's suggested that innovative safety analysis methods be integrated with cost-benefit assessments.

For the formulation of a safety case, it's recommended to use Quantitative Risk Analysis (QRA). QRA offers an objective, structured approach for risk evaluation, provided that it's backed by sound engineering judgement and that the constraints of the data employed are thoroughly understood. QRA can methodically pinpoint the main pathways leading to severe system failure conditions, enabling the implementation of all feasible and practical mitigation measures.

5.2.2 Formal Safety Assessment

Formal Safety Assessment (FSA) is a structured and systematic methodology introduced by the International Maritime Organization (IMO) to enhance maritime safety through risk evaluation and cost–benefit analysis, widely used for evaluating new regulations and comparing alternatives (Psaraftis, 2012). The primary goal of FSA is to create a proactive, methodical framework for ensuring maritime safety.

This goal is achieved through an approach that not only formulates safety measures individually but also integrates them into the wider system. The FSA process involves a comprehensive risk analysis, and a logical, systematic assessment of the costs and benefits associated with mitigating such risks, among other aspects.

The Formal Safety Assessment (FSA) procedure is structured into five distinct stages. The initial stage entails identifying and documenting all potential hazards and situations that might pose risks. Following this is a thorough evaluation of the identified risks. Subsequently, options for controlling these risks are examined. The final stage involves a detailed cost-benefit analysis, as illustrated in Figure 6.1.

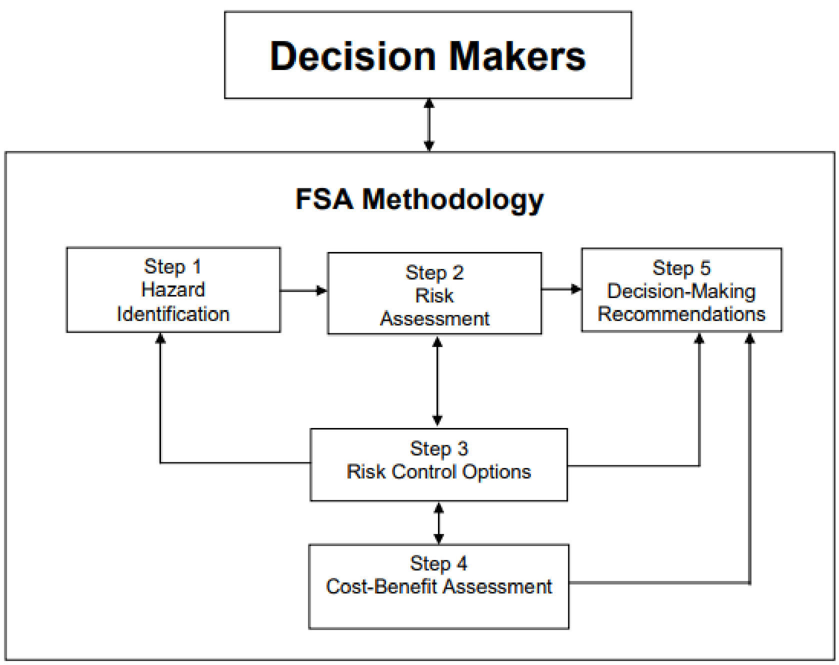


Figure 5. 1: Flowchart of Formal Safety Assessment (IMO, 2010)

5.2.2.1 Hazard Identification

The identification of hazards serves as an instrumental process, playing a crucial role in recognising and prioritising potential dangers in a specific context. This process involves discerning the likelihood and the aftermath of potential accidents or incidents within a particular system or environment. Standard procedures, including data analysis and expert opinions, are adopted to ensure the systematic and comprehensive recognition of risks that could cause harm. Potential hazards are assessed based on their probability of occurrence and potential severity, which, in turn, influences the ranking and management of these risks. This phase also entails a thorough examination of accident scenarios and their associated triggers to pinpoint root causes and prioritise risk mitigation efforts.

5.2.2.2 Risk Analysis

Following hazard identification, the next step in the process is risk assessment. This section delves into a deeper analysis of the sources, triggers, and potential outcomes of identified hazards. Emphasis is placed on high-risk areas, allowing for the exploration and evaluation of factors that impact the level of risk. The formal safety assessment method integrates detailed system conditions and accident characteristics into a quantitative risk estimate. The overall risk is established through an understanding of the frequency and severity of a hazardous occurrence. The equation *Risk = Frequency x Severity* encapsulates the interaction between these two variables, thereby providing a measure of the total risk.

5.2.2.3 Risk Control Options

After risk assessment, this section explores the development of risk control measures (RCMs). These measures vary, encompassing design changes, operational modifications, and employee training programs. The organisation strategically identifies and develops these measures to address both existing and potential future risks. The section discusses the use of the hierarchy of hazard control pyramids in risk control implementation, which includes methods ranging from complete elimination of risk to personal protective equipment.

5.2.2.4 Cost Benefit Analysis

The final phase of the formal safety assessment is a cost-benefit analysis. This section involves the identification and comparative analysis of the costs and benefits associated with each risk control option. The cost-effectiveness of safety improvement measures is quantified using metrics such as the Gross Cost of Averting a Fatality (Gross CAF) and the Net Cost of Averting a Fatality (Net CAF). A comprehensive understanding of the processes behind these metrics is facilitated by references to documents including MSC 72/16, UNDP 1990, and Lind 1996.

Table 5. 1: Cost-effectiveness criteria for NCAF and GCAF (MSC 72/16, UNDP 1990, and Lind 1996.)

	NCAF (US $)	GCAF (US $)
Criterion covering the risk of fatality, injuries, and ill health	3 million	3 million
Criterion covering only risk of fatality	1.5 million	1.5 million
Criterion covering only risk of injuries and ill health	1.5 million	1.5 million

5.2.3 Risk-Based Design

Designing is the creation and development of a plan for a product, involving striking a balance between multiple objectives related to feasibility, performance, cost, aesthetics, and logistics. Specifically, in the realm of ship design, this balance is paramount given the high-risk nature of the shipping industry. Innovative strategies and procedures that tackle significant risk factors during the early stages of design are crucial. Applying this approach early in the design process, when modifications can be made at a minimal cost, is most effective. By making safety a fundamental performance goal, the designer, potentially in conjunction with shipowners or management, can address the root causes of significant hazards in a cost-effective and efficient manner.

Altering the design process in such a way, brings an additional benefit: it reduces the necessity to entirely replicate past successful designs. The services offered by new ships are only faintly similar to those from 15 or 20 years ago. For instance, modern cruise liners capable of carrying over 5000 passengers and about 3000 crew members have recently been introduced. Managing such a large concentration of people on a single marine structure requires exceptional skills, creativity, and innovation, and it cannot solely rely on past experiences. Due to existing design constraints, such as regulation implementation and compliance, the safety performance of contemporary maritime vehicles is substantially compromised.

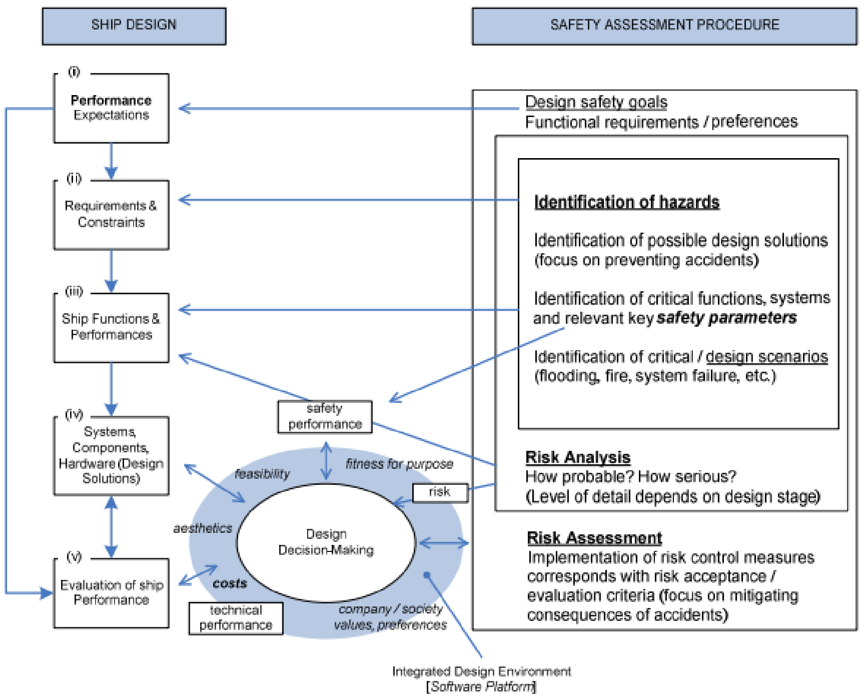


Figure 5. 2: High level risk-based design, (Vassalos, 2006)

Risk-based ship design fundamentally integrates risk evaluation into the design process, systematically working towards mitigating potential risks to life, property, and the environment, as illustrated in Figure 6.2. Several crucial factors need to be considered while addressing risk-based ship design (Vassalos et al. 2006). One such factor is that risk is often associated with disastrous events, which distinctly separates it from reliability techniques that mainly tie into maintenance practices throughout a ship's lifespan. Tragic events, such as collisions, grounding, fire, sinking, and foundering, occurring consecutively or concurrently during ship operations have led to catastrophic outcomes.

Moreover, directly addressing safety necessitates its quantification; in this context, risk is perceived as the measure of safety. Evaluating it during the design phase, especially during the initial stages, becomes paramount. This is when most of the ship's fundamental features are formed and can be modified with relative ease. The goal of risk-based design is to harness the power of robust engineering practices, informed decisions, advanced tools, and data. These elements are not only key to innovation but also integral to a Quantitative Risk Analysis (QRA).

The incorporation of a risk-based approach in ship design has been transformative for the industry. It offers a systematic procedure for assessing and managing risks, which subsequently leads to safer ships and better results for all involved parties.

5.3 Safety Analysis Methods applied to the risk-based approach.

In applying the risk-based approach to safety, the methodologies for safety analysis become instrumental. These tools are tailored to elucidate potential hazards and assess their possible impacts, which equips engineers with valuable insights for formulating informed and effective strategies to mitigate or even completely eradicate these risks. Furthermore, risk analysis plays a pivotal role in this process.

Risk analysis involves the systematic use of available information to determine how often specified events may occur and the magnitude of their likely consequences. This method helps to understand the nature of the risk, potential harm, and the urgency of controlling the hazard. It provides a structured approach for understanding uncertainty and making decisions in complex situations where there are competing objectives, and the outcomes are uncertain.

On examining the three approaches mentioned above - safety case, FSA, and risk-based - it is evident that hazard identification and risk analysis are not just important, but rather indispensable elements. For a special case like ship recycling, where safety considerations are paramount, these techniques hold considerable significance. It is therefore important to identify an appropriate methodology tailored for this unique scenario. To this end, we turn our attention towards selecting the most suited technique for hazard identification and risk analysis in the context of ship recycling.

We identified that among the tools typically used in hazard identification are Failure Mode and Effects Analysis (FMEA), Hazard and Operability studies (HAZOP), What-If Analysis Technique, and a method specially designed for ship recycling context: The three-step method. Each of these methodologies has its own set of advantages and limitations, making their selection highly dependent on the unique aspects of the scenario under consideration. Moreover, within the scope of risk analysis, the usual methodologies employed encompass Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Risk Contribution Tree (RCT), Influence Diagrams, and Bayesian Networks.

This part below thus focuses on evaluating and identifying the most suitable methods for hazard identification and risk analysis in the ship recycling context. We aim to bolster the safety parameters within this specific industry, aligning it with the risk-based approach.

5.3.1 Failure Mode and Effect Analysis (FMEA)

FMEA is a robust and efficient tool that excels in identifying the underlying causes of failures, determining methods of detection, and designing strategies to prevent or mitigate their effects to manage potential failure sources. Moreover, it provides the means to evaluate potential failures and select corrective actions that can reduce their severity and frequency. The application of FMEA spans systems, designs, processes, or services, uncovering all possible failures within these contexts. The assessment of risk factors relies on the frequency, severity, and detection of failures (Lin, 2014). This method has found widespread use in risk management.

Basuki et al. (2017) employed FMEA to pinpoint all failures and their effects in the dry bulk unloading process, and Fariya (2017) used FMEA to determine all failures and their implications in the entire ship recycling process, with a case study in Indonesia. Both studies utilised field observations, worker questionnaires, and expert interviews to compile the list of hazards involved in each process. Moss and Kurty in 1983 performed a reliability analysis of the preliminary design of a Tension Leg Platform (TLP) using FMEA and FTA, effectively identifying and examining all possible failures and their impacts.

5.3.2 Hazard and Operability studies (HAZOP)

HAZOP is a systematic and meticulous examination technique used for planned or ongoing operations or processes. At the commencement of the study, the team formulates a conceptual model or a design representation of the system or operation in question. One of the primary goals of a HAZOP analysis is to detect and assess any lingering risks in a planned operation or process that might have been overlooked or unaccounted for in the earlier project phases. Deacon et al. (2010) implemented HAZOP to conduct a risk analysis of human errors in offshore emergency musters, using this tool to document types of failures, potential consequences, and safety measures. They developed a HAZOP of the muster procedure to streamline the selection and evaluation of potential safety measures for reliability.

5.3.3 What-if Analysis

What-If analysis is a qualitative methodology that employs a flexible and loosely structured series of questions to hypothesize potential disturbances that could lead to accidents or problems with system performance. It predicts what could go wrong, the potential outcomes of these situations, and assesses the ramifications of these potential occurrences (Ayyub, 2003). Anand M. Hiremath (2016) implemented the What-If analysis to scrutinize potential risks associated with each job activity in the context of ship recycling. This analysis hinges on "what if" scenarios for any situation in an industrial facility and each operation or process. It primarily delves into what could potentially disrupt a system and, should any activity stray from its usual course, what fallout could result from this deviation.

5.3.4 The Three Step Methods

The three-step approach to hazard identification in the ship recycling industry starts with the preparation of a hazard inventory. This inventory acts as a base, containing an exhaustive list of all potential hazards associated with ship recycling processes. Following inventory creation, the focus shifts to hazard assessment. This step involves a systematic evaluation of each listed hazard, considering variables like their potential severity, frequency, and detectability. This assessment culminates in a prioritized list of hazards requiring attention. Finally, with a clear understanding of the major hazards and their possible impacts, risk control measures are identified. This structured three-step method provides a practical approach to managing hazards in the ship recycling industry, emphasizing the critical role of systematic hazard identification and risk control (Kurt, 2016).

5.3.5 Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is a practical, constructive method used for identifying and analysing potential accident scenarios, along with associated safety measures that occur following an initiating event. It allows for the visualisation of event sequences leading to the success or failure of a management system. Utilising a tree structure, an Event Tree, this method showcases various possible outcomes, and in some instances, probabilities. The process commences with the prediction of an Initial Event (IE), followed by an assessment of whether this event might lead to additional risks and if existing controls can manage the accident.

An example of ETA usage is demonstrated in a study by Asif Raiyan and colleagues (2017). They employed an event tree to illustrate how a single factor, in combination with others or independently, could lead to marine accidents in the Bangladeshi maritime industry. Their event tree, representing the sequence of events, is set to assist future researchers and system designers in pinpointing and removing contributing elements to marine accidents, thereby aiming to lower the exceedingly high frequency of these catastrophes.

5.3.6 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is an instrumental technique for risk analysis as it allows for a systematic examination of various pathways leading to a system failure. Starting from a top-level undesirable event and working its way downward, it effectively identifies the combinations of lower-level events that could result in failure. FTA aids in recognizing the root causes, such as hardware faults or human errors, contributing to system failure. Moreover, it facilitates the quantitative evaluation of risk by assigning probabilities to each event, thereby aiding in understanding the likelihood of failure occurrence. Understanding the contributing factors and their associated probabilities allows organisations to prioritize their mitigation measures, targeting the most significant risks first. Additionally, FTA provides a valuable platform to assess the effectiveness of safety measures, exploring whether the measures in place are sufficient to reduce the risk of the top-level event. In summary, FTA serves as a powerful tool in risk management, offering a means to systematically analyse and mitigate risks in complex systems.

5.3.7 Risk Contribution Tree (RCT)

RCT is a qualitative method that plays a vital role in risk analysis by examining potential disruptions that may lead to accidents or system performance problems. It explores what could go wrong, and the potential consequences of those situations, and evaluates the implications of such occurrences. Similar to the "what-if" analysis, it assesses potential deviations in an operational process and the resulting effects of such deviations.

Furthermore, in the realm of risk analysis, RCT serves as an instrumental tool to understand and quantify the contributions of individual risks to an overall risk profile. Its primary function is to systematically dissect complex risk scenarios, breaking them down into manageable and understandable units. It does this by visualizing the hierarchical relationship between an overarching risk and its contributing factors, thus enabling a deeper understanding of the complexities involved in managing the multifaceted risks inherent in industrial processes.

5.3.8 Influence Diagram

The influence diagram is a technique that models the network of factors influencing a particular event. This technique plays a vital role in risk analysis as it provides a relationship between operational failures, their immediate causes, and the underlying organisational and regulatory influences. The Influence Diagram approach is grounded in decision analysis and is particularly beneficial when empirical data is limited or non-existent. As such, it relies heavily on expert judgments to identify all the contributing factors that explain variances in marine risk profiles.

In essence, an Influence Diagram is a graphic representation of key identified risks, decisions, and outcomes that shows their interconnectivity and relative order. It provides a more holistic view of the risk scenario by acknowledging the impact of various factors, including human, organisational, and regulatory aspects. The primary objective of an Influence Diagram is to engage experts and key personnel in the decision-making process, to create a universally understood model of decision factor interactions, and to highlight key uncertainties that need to be modelled either qualitatively or quantitatively. This makes it a particularly useful tool for risk analysis, helping stakeholders understand and navigate the complexities of hazardous decision-making processes.

5.3.9 Bayesian Network

Bayesian Network (BN) is an advantageous tool used in the field of risk analysis due to its exceptional capacity to model and evaluate probabilities of various outcomes under given conditions or events. With its power to simulate intricate, uncertain situations, it integrates both tangible data, like failure rates, and subjective evaluations, such as expert viewpoints. This amalgamation of objective and subjective data provides a broad, yet detailed view of the potential risks involved. As BN operates on a probabilistic foundation, it's capable of offering a quantitative measure of the risks related to different hazards. This quantification of risk, coupled with its ability to display the likelihood and potential severity of various outcomes, makes it an indispensable tool in the realm of risk analysis. BN is particularly effective in complex systems where there are numerous interacting factors and dependencies, and the understanding of these intricate relationships can provide a more informed, comprehensive risk assessment.

5.4 Selection of Safety Analysis Methods for Ship Recycling Case

The selection of appropriate hazard identification methods for ship recycling required a systematic and expert-driven approach due to the industry's unique and complex characteristics. To ensure a robust and unbiased selection process, an internal workshop was designed. The primary goal of the workshop was to leverage expert judgment to evaluate different methods based on specific, industry-relevant criteria. This section outlines the design of the workshop, the criteria development process, and how expert opinions were systematically incorporated into the decision-making framework.

5.4.1 Workshop Design and Expert Evaluation Framework

- **Objectives and Workshop Framework**

  The main objective of the workshop was to identify the most suitable hazard identification methods for application in ship recycling. The workshop was structured to facilitate a comprehensive evaluation process, divided into the following stages:

  1. Context Setting: Introduce the challenges and specific needs of the ship recycling industry to ensure all participants have a shared understanding.
  2. Criteria Definition: Collaboratively define the evaluation criteria that reflect the unique requirements of ship recycling.
  3. Method Review: Present and discuss potential hazard identification methods.
  4. Expert Evaluation and Scoring: Use a systematic scoring process to assess each method based on the agreed criteria.
  5. Consensus Building: Facilitate discussions to resolve differences in expert opinions and reach a consensus.

- **Composition of the Expert Panel**

  The expert panel was carefully selected to include professionals with diverse and relevant expertise, ensuring a comprehensive evaluation from multiple perspectives. The panel consisted of:

  1. Safety Engineers: With experience in hazard identification and safety assessments in industrial settings.
  2. Risk Analysts: Experts in both qualitative and quantitative risk evaluation techniques.

3. Ship Recycling Practitioners: Individuals with practical, hands-on knowledge of ship dismantling operations and associated risks.
4. Academic Researchers: Specialists with insights from relevant studies and previous projects.

The varied backgrounds of the panel members provided a balanced view, integrating both theoretical knowledge and practical experience.

- **Development of Evaluation Criteria**

A key part of the workshop was defining a set of criteria that would guide the assessment of hazard identification methods. The criteria needed to reflect the specific challenges and needs of the ship recycling industry. To establish these criteria, a facilitated discussion was held where experts shared their insights based on their field experience. This collaborative session led to the identification of several key factors:

1. **Understandability**: The ease with which the method can be understood and used by personnel of different expertise levels.
2. **Ease of Use**: Practicality and straightforwardness in real-world application without requiring extensive technical training.
3. **Flexibility**: The ability of the method to adapt to various scenarios and different phases of ship recycling.
4. **Data Requirements**: The extent of data needed for effective implementation and the method's capability to function when data is limited.
5. **Comprehensive Risk Assessment**: The method's ability to identify a wide range of hazards and assess their potential impacts.
6. **Time Efficiency**: The speed at which the method can be applied, given the dynamic and fast-paced nature of ship recycling operations.

Each criterion was discussed and refined until a consensus was reached on its importance and relevance. The final criteria were assigned a weighted score based on expert input, reflecting their priority in the selection process.

- **Method Evaluation Process**

The next stage involved a systematic review of potential hazard identification methods. The experts were provided with detailed descriptions of the shortlisted methods, including their typical applications, strengths, and limitations. This stage of the workshop included:

1. Presentations of Methods: Detailed overviews of each method (e.g., FMEA, HAZOP, What-If Analysis, and Three-Step Method) were presented, along with examples of their use in similar industrial contexts.

2. Individual Scoring: Experts were asked to independently score each method against the predefined criteria using a standardized scale (e.g., Low, Medium, High). The use of individual scoring helped to minimise bias and capture a range of perspectives.

- **Expert Judgment and Consensus Building**

  Following the individual scoring process, the results were collated and presented back to the panel for group discussion. This session was designed to facilitate open dialogue among the experts, allowing them to explain their reasoning and provide justifications for their scores. Key aspects of this session included:

  1. Discussion of Divergent Opinions: Any significant differences in scores were highlighted, prompting detailed discussions. This process helped clarify misunderstandings, allowed experts to reconsider their assessments, and contributed to a deeper understanding of the strengths and weaknesses of each method.
  2. Use of Real-World Examples: Experts were encouraged to refer to their own experiences and previous projects, such as the DIVEST project, to provide context and practical insights into how each method might perform in the ship recycling industry.
  3. Iterative Refinement: The scoring process was iterative, with experts revisiting their ratings after group discussions. This allowed for adjustments based on new insights and collective reasoning, fostering a consensus-driven outcome.

5.4.2 Selection of Hazard Identification Methods

Ship recycling is a complex process that involves numerous procedures, various types of equipment, and many workers. Because of its multifaceted nature, several hazard identification methods are essential for comprehensive risk assessment and safety enhancement. Here are the characteristics of the hazard identification methods required for the ship recycling case:

- Efficiency and Ease of Use: Due to the multifaceted nature of ship recycling, the methods employed should be easy to understand and apply. They should also not be overly time-consuming, as time is a crucial factor in the industry.
- Flexibility: The methods should be versatile enough to handle the wide variety of processes, materials, and equipment involved in ship recycling. They should be capable of identifying hazards in different parts of the process, from design and construction to operation and disposal.
- Comprehensive Risk Assessment: The methods should not only identify potential hazards but also assess their potential impacts on health, safety, hazardous materials, and the environment.
- Expertise Requirements: Given the specialised nature of ship recycling, the methods should be approachable for those with a wide range of expertise levels. It should not necessitate extensive technical knowledge or training to understand and implement the methods.
- Data Requirements: The methods should make good use of available data but also be able to function effectively when data is limited or lacking. In the case of ship recycling, historical data may not always be readily available, and thus methods that can incorporate expert judgment or qualitative assessments can be highly beneficial.
- Qualitative and Quantitative Analysis: The ideal methods would provide both qualitative descriptions of potential accidents and quantitative risk characterisations. This balance allows for a more holistic understanding of the potential hazards and their potential impacts.
- Applicability: The methodologies should be applicable in various stages of the ship recycling process - from the design phase, facilities improvement, to operation.

Below is the comparative analysis result.

Table 5. 2: Comparative analysis of hazard identification methods

Methods	Understandability	Ease of Use	Time Efficiency	Flexibility

FMEA	High: The process is logical and follows a clear sequence of identifying failure modes and their effects.	Medium: While it does require a structured approach, it's quite straightforward once understood.	Medium: Can be time-consuming due to its comprehensive nature.	High: Can be applied to various processes, components, and stages of operation.
HAZOP	High: It uses systematic and creative ways to identify hazards that might not be found by other means.	Medium: It needs a structured approach but can be managed once familiar with the method.	Medium-High: This can be time-consuming because it requires a detailed analysis of the system.	High: Suitable for all types of processes and operations, very relevant for chemical and process industries.
What-If	High: The process is straightforward, based on questioning and brainstorming potential hazards.	High: It is easy to apply and doesn't require a structured or complex approach.	High: It's a fast process if conducted by experienced personnel.	High: It can be used in various scenarios from the design phase to operation.
Three Step	High: Involves straightforward steps of hazard identification, hazard evaluation, and hazard control.	High: Very easy to use given its simple, systematic approach.	High: The method is not too time-consuming and provides rapid results.	Medium: Although flexible, it may not be as detailed as other methods.
Methods	Data Requirement	Expertise Requirement	Qualitative/Quantitative Approach	Suitability for Ship Recycling
FMEA	High: Detailed data about the processes and equipment are needed.	Medium: Requires expertise about the process and equipment under review.	Both: Can be used for qualitative identification of failure modes and for 3quantitative risk assessment of the identified failures.	High: With the necessary expertise and data, FMEA can thoroughly identify potential hazards in ship recycling.

HAZOP	High: Requires a complete set of process flow diagrams, plot plans, equipment layouts, and operating procedures.	Medium: It necessitates the team to have an understanding of the process being investigated.	Qualitative: Mainly focused on qualitatively identifying potential hazards and operability problems.	High: Given the process-oriented nature of ship recycling, HAZOP can be quite effective in identifying hazards.
What-If	Medium: Depends on the experience and knowledge of the participants.	Medium: Requires experts who are knowledgeable about the process and equipment.	Qualitative: Based on generating scenarios and exploring possible outcomes.	High: Given the unpredictability in ship recycling processes, this method can provide insight into various potential hazards.
Three Step	Low-Medium: It doesn't require as much data, mainly relies on the knowledge and experience of the analyst.	Medium: Requires a basic understanding of the process and hazards involved.	Qualitative & Quantitative Can be used for both, primarily involves identifying and assessing hazards based on knowledge and experience.	High: Given its simplicity and practicality, it can be effectively used in the ship recycling industry.

Upon reviewing the four hazard identification methods - FMEA, HAZOP, What-If, and the Three-Step Method, each exhibits certain strengths and potential limitations. However, considering the specific characteristics and requirements of the ship recycling context, the Three-Step Method seems to be the most suitable approach. It provides an easy-to-use and time-efficient means of hazard identification that does not require extensive data or complex procedural structures. This makes it ideal for use in the dynamic, process-oriented environment of ship recycling, where conditions and hazards may vary greatly and unpredictably. However, it's essential to note that the Three-Step Method does require an up-to-date and detailed list of processes, hazards, and it causes specific to the current ship recycling yard. This requirement can be seen as a limitation as the quality of the hazard identification relies heavily on the accuracy and completeness of these lists.

But on the whole, the Three-Step Method provides an adaptable approach to efficiently address the wide range of potential hazards inherent in ship recycling operations. The method's limitations can be mitigated by periodically reviewing and updating the lists to reflect current conditions and practices.

The selected method has been presented to another expert and they agreed (initial validation). They were in agreement

5.4.3 Selection of Risk Analysis Methods

The selection of the right risk analysis methods for the ship recycling industry relies on the methods' alignment with the following characteristics:

- Robustness: The method should be capable of handling the diverse and dynamic range of hazards that can occur in the ship recycling industry. This includes everything from immediate physical risks to long-term environmental consequences.
- Flexibility: Given the dynamic nature of ship recycling processes, the risk analysis method should be flexible enough to accommodate changes and adapt to new scenarios and conditions.
- Comprehensive: It is crucial that the method is capable of evaluating all facets of risk, including safety, health, environmental impacts, and potential hazards associated with materials.
- Efficiency: The method should provide results in a timely manner to ensure swift action can be taken when necessary. It should also be easy to implement, avoiding overly complicated processes that could slow down analysis.
- Qualitative and Quantitative Analysis: Both qualitative and quantitative risk assessments are crucial. The method should provide descriptive insights into risks and their implications while also offering numerical risk levels for prioritization and management.
- Detail-oriented: The method should delve deep into each risk factor to identify root causes and underlying issues. This facilitates the implementation of effective preventive and control measures.
- User-friendly: The method should be intuitive and easy to use, encouraging regular and widespread usage among workers and decision-makers in the ship recycling industry.

Table 5. 3: Comparative analysis of risk analysis methods

Method	Robustness	Flexibility	Comprehensive	Efficiency
FTA	Medium: FTA exhibits medium robustness due to its binary nature, i.e., an event has either occurred or not.	High: FTA is flexible enough to handle complex systems like ship recycling and can adapt to changes in the process.	High: FTA is comprehensive in analysing the failure modes and their effects but lacks in identifying the causative factors.	Medium: Efficiency is medium as it requires extensive data and expert involvement.
ETA	High: ETA exhibits high robustness as it explores all potential outcomes of an event.	High: ETA is highly flexible to handle different scenarios and changes in the process.	High: ETA comprehensively evaluates all potential outcomes and their associated risks.	High: ETA is efficient due to its graphical representation and understanding of sequential events.
RCT	Low: RCT has low robustness as it is subjective and based on expert opinions.	Medium: RCT exhibits medium flexibility as it can handle different scenarios but is limited in modelling complex systems.	Medium: RCT provides a medium level of comprehensive risk assessment, focusing mainly on identifying high-risk elements.	Low: RCT's efficiency is low due to its heavy reliance on expert involvement.
Influence Diagram	Medium: Influence diagrams show medium robustness as they depend on expert judgment.	High: Influence diagrams offer high flexibility as they can represent a wide range of risk factors and their interactions.	High: These diagrams provide a comprehensive view of all the factors affecting risk.	Medium: The efficiency of influence diagrams is medium as they can be time-consuming to develop.
Bayesian Network	High: Bayesian Networks are highly robust as they are based on sound mathematical principles and can handle uncertainty.	High: Bayesian networks offer high flexibility as they can model a wide variety of scenarios, even when data is sparse.	High: These networks can comprehensively model risk by accounting for all relevant variables	Medium: The efficiency of Bayesian networks can be medium to high depending on the complexity of the network.

			and their interdependencies.	
Method	Qualitative & Quantitative	Detail-oriented	User-friendly	
FTA	Quantitative: FTA is mainly quantitative as it provides numerical risk estimates.	High: FTA's detail-oriented nature is evident from its tree-structure analysis.	Medium: User-friendliness is medium as it requires expertise to develop and interpret the tree.	
ETA	Both: ETA allows both qualitative and quantitative analysis of the events and their impacts.	High: ETA is highly detail-oriented as it explores every branch of potential outcomes.	High: ETA is user-friendly because of its simple tree structure which is easy to develop and interpret.	
RCT	Qualitative: RCT mainly provides qualitative analysis.	Medium: RCT is medium in detail orientation, focusing on higher-level risk contributors.	Low: RCT's user-friendliness is low due to its subjective nature and complexity.	
Influence Diagram	Both: Influence Diagrams allow both qualitative and quantitative analysis.	High: Influence diagrams provide a detailed representation of risk factors and their interconnections.	Medium: Understanding and interpreting influence diagrams may require a certain level of expertise.	
Bayesian Network	Both: Bayesian networks support both qualitative and quantitative risk analysis.	High: Bayesian networks are highly detail-oriented, representing complex dependencies between variables.	Medium: Understanding and interpreting Bayesian networks requires a certain level of expertise.	

Based on these characteristics, Event Tree Analysis (ETA) is found to be the most suitable method for risk analysis in the ship recycling industry. It shows high robustness, flexibility, and comprehensiveness. Furthermore, it is efficient, supports both qualitative and quantitative approaches, is highly detail-oriented, and user-friendly. Thus, ETA is considered as the preferred method for risk analysis in ship recycling scenarios.

The complexities of the ship recycling industry necessitate a multi-faceted approach to risk analysis, as the distinct characteristics of each method can address different aspects of risk. While individual techniques have their limitations, the combination of various methods can offer a comprehensive perspective and yield more relevant results. As detailed in Chapter 2, the ship recycling industry is facing several major challenges that need to be addressed:

- There is a significant lack of planning and risk awareness among ship recycling employees at all levels. This gap can be bridged with the implementation of systematic hazard identification methods, involving a team of experts from related fields to compensate for the employees' limited safety knowledge.
- It is critical to identify and prioritize the most hazardous tasks that require immediate improvement. This can be achieved by developing a structured approach starting with a detailed identification of the process flow and job tasks within each ship recycling zone, followed by a thorough hazard screening and identification of causal factors.
- Addressing safety issues while maintaining profitability is another important consideration. Implementing safety measures and adhering to guidelines should not compromise the industry's existing profits. To ensure this, it is crucial to factor in the cost-effectiveness of the proposed safety measures.

Given these complexities, a method that combines efficient hazard identification with cost-benefit calculation is ideal. The process would involve a simulation for each risk control option, allowing for the calculation of efficiency gained. Such a combination would ensure comprehensive risk analysis, safeguard worker safety, and maintain operational profitability, thereby providing a holistic solution to the challenges in the ship recycling industry.

The selection of appropriate hazard identification and risk analysis methodologies in this chapter forms the foundation for the next phase of the framework. Chapter 6 builds upon these findings by translating the identified hazards, causal factors, and control measures into a discrete-event simulation model. This integration ensures that the simulation parameters reflect realistic operational and safety conditions observed in ship recycling yards, creating a direct link between risk assessment and performance modelling. Notwithstanding these strengths, certain practical constraints should be noted. The Three-Step Method relies on current, sufficiently detailed process information; where data are light or informal practices prevail, some hazards may be under-represented. ETA, while robust and transparent, assumes clearly defined initiating events and depends on expert judgement for probabilities, introducing some subjectivity. These risks are mitigated by triangulating expert inputs, periodic updates to the hazard inventory, and (in Chapter 6) linking the assessment to simulation outputs for sensitivity and consistency checks.

5.5 Chapter Summary

This chapter provided an in-depth examination and comparison of the risk-based approach and the safety analysis methodologies, expanding upon the discussions from previous sections. Initially, we delved into the core elements of the risk-based approach, highlighting its utility and application in the context of the ship recycling industry. We particularly emphasized its potential for aiding the decision-making process, by identifying and evaluating the uncertainties and potential risks associated with each decision. Following this, we critically reviewed a range of safety analysis methodologies, including FMEA, HAZOP, What-If Analysis, the Three Step Method, FTA, ETA, RCT, Influence Diagram, and Bayesian Network. Through an analytical lens, these methodologies were evaluated based on their appropriateness for the ship recycling case, taking into account factors such as ease of use, flexibility, comprehensiveness, and efficiency. Finally, based on a detailed comparative analysis, we concluded that the Event Tree Analysis (ETA) method is the most suitable risk analysis methodology for ship recycling, owing to its robustness, flexibility, and user-friendliness. Furthermore, the Three Step Method emerged as the most suitable approach for hazard identification, given its simplicity, efficiency, and comprehensive approach.

Chapter 6. Modelling and simulation for the ship recycling process

6.1 Chapter Overview

Building on the risk identification and hazard analysis results presented in Chapter 5, this chapter focuses on developing a discrete-event simulation (DES) model to evaluate productivity and operational performance in ship recycling yards. The parameters and scenarios for the simulation are directly derived from the risk assessment findings, ensuring that the model accurately reflects real-world operational and safety conditions. This integration forms the first step of the iterative framework, where risk assessment informs simulation design, and simulation results later feed back into the refinement of risk control strategies, as described in Chapter 7.

In this chapter, the focus is on utilising modelling and simulation techniques to analyse and optimise the ship recycling process. The key characteristics of Complexity and Interdependence of Operations and Compliance with Regulations are prioritised as they have a significant impact on the efficiency and success of ship recycling. An overview is provided for three modelling techniques: System Dynamics (SD), Agent-Based Modelling (ABM), and Discrete Event Simulation (DES). Through a comparative analysis, DES is identified as the most suitable technique for capturing the complexities of the ship recycling process and ensuring compliance with regulations. This chapter establishes a strong foundation for subsequent analysis by selecting DES as the modelling technique of choice. The goal is to develop and implement a DES model that will provide valuable insights into the ship recycling process, identify bottlenecks, and propose strategies for improved efficiency and compliance.

6.2 Modelling concept applicable to ship recycling

Modelling is a fundamental concept utilised across numerous disciplines to represent the reality of a process or system in a simplified and understandable way (Law, 2007). It is a tool to illustrate, analyse, and predict the behaviour of complex systems. Models are structured representations that describe the essential features, behaviours, and functions of a real-world process or system. They provide the means to analyse different scenarios, perform "what-if" analyses, and predict the impact of various factors on the outcomes of interest (Banks et al., 2009).

At its core, modelling is a method of abstraction that translates real-world complexities into a structured and more manageable format (Giaglis, 2001). This tool is essential for the comprehension of multifaceted processes and provides a platform to evaluate the dynamics, interdependencies, and potential bottlenecks within a system (Robinson, 2008).

The benefits of modelling are multifaceted and extend across various industries and applications. From Optimising process steps to managing resources efficiently, improving safety measures, and reducing environmental impact, modelling serves as a powerful tool for systematic analysis and improvement (Williams et al., 2013).

Given the importance of modelling in managing complex processes, it is necessary to examine its application within the ship recycling process. The subsequent sections will discuss the specific modelling techniques relevant to ship recycling, evaluate their strengths and limitations, and detail the rationale for the selection of a particular modelling approach for this research (Balakrishnan et al., 2016).

In the context of ship recycling, modelling plays an essential role in structuring the complexity of the process and providing insights to enhance efficiency and sustainability. The ship recycling process comprises various interrelated tasks, including inventory preparation, decontamination, dismantling, waste management, and materials recovery. The complexity of these tasks, coupled with variations in the types and sizes of ships and diverse recycling regulations and guidelines, necessitates effective modelling approaches to optimise the process.

Modelling, in essence, is a simplification of reality, presenting a systematic and logical representation of an object, system, or concept. When applied to ship recycling, it translates the multifaceted process into a structured, manageable form. This conversion allows researchers and industry professionals to better comprehend and evaluate the process dynamics, interdependencies, and potential bottlenecks. It serves as an excellent tool for exploring "what if" scenarios, enabling them to anticipate outcomes under various conditions without having to implement and observe these changes in real-life—costly in terms of time, money, and environmental impact.

The benefits of modelling for complex processes like ship recycling are manifold:

- Optimising Process Steps: Through modelling, one can identify the most efficient sequence of operations, reducing waste and saving time. It can provide insights into how different stages of the recycling process influence each other and where improvements can be made.
- Managing Resources: Effective modelling helps in proper resource allocation, ensuring the optimal utilisation of manpower, machinery, and time. It can help pinpoint where resources might be over- or under-utilised.
- Improving Safety: Modelling can highlight potential safety hazards in the recycling process, allowing pre-emptive measures to be put in place. This is crucial given the inherent risks associated with ship recycling, including exposure to toxic materials and dangerous working conditions.
- Reducing Environmental Impact: A well-structured model can assist in identifying environmentally damaging steps in the recycling process. By exploring alternative approaches through the model, one can devise more eco-friendly methods of operation.

Given the importance of modelling in managing complex processes, it is necessary to examine its application within the ship recycling process. The subsequent sections will discuss the specific modelling techniques relevant to ship recycling, evaluate their strengths and limitations, and detail the rationale for the selection of a particular modelling approach for this research.

6.3 Exploration of different modelling and simulation techniques

After discussing the concept and significance of modelling, it's important to note that simulation works hand-in-hand with modelling. Simulation is the process of implementing a model over time (Law, 2007). It allows us to analyse the model in an operational time dimension and observe the progression and interaction of components within the model. As such, the evaluation and selection of an appropriate simulation technique is a critical complement to the modelling process. It provides the necessary platform to evaluate and predict the performance of the proposed model under different scenarios (Banks et al., 2009).

Several modelling and simulation techniques have found relevance in complex systems like ship recycling. These include System Dynamics, Agent-Based Modelling, Process-Based Modelling, and Discrete Event Simulation (Balakrishnan et al., 2016). Each of these techniques has unique characteristics, strengths, and limitations that make them more suitable for certain applications

(Giaglis, 2001; Robinson, 2008). As such, understanding each of these techniques is crucial in making an informed decision on the appropriate method for a given scenario.

6.3.1 System Dynamics (SD)

System Dynamics (SD) is a modelling approach used for understanding the behaviour of complex systems over time. It involves the use of stocks, flows, feedback loops, and time delays to describe the structure and dynamics of systems (Forrester, 1961; Sterman, 2000). Originally conceptualized by Jay Forrester in the mid-20th century at the Massachusetts Institute of Technology, SD focuses on understanding how system structure influences system behaviour (Forrester, 1961). At its core, it is about understanding the feedback loops - both positive (reinforcing) and negative (balancing) - that drive system dynamics.

SD modelling requires time-series data that reflects the changes in system variables over time. This might include data on the number of ships arriving for recycling, the rate at which different stages of the recycling process are completed, and the accumulation of different materials over time (Radzicki and Taylor, 2008).

SD modelling is particularly effective for understanding complex systems characterized by interdependencies, delays, and feedback loops. It provides a high-level, holistic view of the system and its dynamics, allowing for the exploration of long-term trends and the impacts of policy interventions (Sterman, 2000). SD models can be used to conduct scenario analyses, test assumptions, and develop strategies for improving system performance. Its application to ship recycling can help identify bottlenecks, inefficiencies, and unintended consequences of policy decisions.

While SD provides a high-level view of the system, it may not capture the detailed interactions and heterogeneity that can be represented in other modelling approaches like ABM. It requires a good understanding of the system's structure and dynamics, and accurate time-series data, which can be challenging to acquire. Finally, the complexity of SD models can make them difficult to communicate and understand, especially for non-experts (Forrester, 1961).

SD has been used in a wide range of fields, including business management, public policy, environmental studies, and healthcare. In business, SD models have been used to understand the dynamics of supply chains, project management, and market growth (Sterman, 2000). In public policy, SD models can be used to simulate the impacts of different policy options and understand complex issues such as climate change, urban planning, and economic development (Forrester, 1969; Richardson, 2011). In healthcare, SD models have been used to simulate the spread of diseases and the impacts of healthcare policies (Homer and Hirsch, 2006).

6.3.2 Agent-Based Modelling (ABM)

Agent-based modelling (ABM) is a computational method that simulates the actions and interactions of autonomous agents (both individual or collective entities such as organisations or groups) with a view to assessing their effects on the system as a whole (Gilbert, 2008; Macal and North, 2010). ABM allows for the exploration of complex system dynamics emerging from individual behaviours, interactions, and learning.

ABM requires detailed data about the characteristics and behaviours of individual agents, as well as rules governing agent interactions (Railsback and Grimm, 2011). The data needed for an ABM can include attributes, behaviours, and decision-making processes of agents. In the context of ship recycling, this might include attributes of the workers (such as skill level), their behaviours (such as their work patterns), and the rules governing how they interact with each other and the environment.

ABM is particularly useful for studying complex systems where individual behaviours and interactions play a critical role. It enables the representation of heterogeneity among agents, adaptation, learning, and complex interaction patterns (Bonabeau, 2002). It allows for the exploration of emergent phenomena, i.e., outcomes that arise from the interactions of individual agents and that are not predictable by looking at the agents alone. This could be particularly relevant for ship recycling, where the outcome of the recycling process is a result of the interactions of a multitude of factors, including the behaviours of the workers, the properties of the ship, and environmental conditions.

The detailed data requirements, the need for an in-depth understanding of agent behaviours and interactions, and the computational demands make ABM a resource-intensive method. Additionally, validating ABM can be challenging because of the emergent phenomena and the fact that these models often include a stochastic (random) component (Gilbert, 2008).

ABM has been widely used in various fields such as ecology, economics, and social sciences. In ecology, it is used to simulate the behaviours of animals and their interactions with the environment to study issues like population dynamics and habitat use (Grimm and Railsback, 2005). In economics, it's applied to model the behaviour of consumers, firms, and markets to understand economic phenomena such as market dynamics and economic crises (Farmer and Foley, 2009). In social sciences, it is used to model social processes, including opinion formation, cultural evolution, and social network formation (Macy and Willer, 2002).

6.3.3 Discrete Event Simulation (DES)

Discrete Event Simulation (DES) is a method that models the operation of a system as a sequence of distinct events in time (Banks et al., 2009; Law, 2007). The emphasis is on the system's state changes at discrete points in time, giving DES its name. This approach is especially effective for systems with events occurring at irregular intervals, leading to state changes. Its wide applicability spans sectors like manufacturing, healthcare, transportation, computer science, and environmental planning (Mustafee, 2012; Robinson, 2004; Schruben, 2010).

DES typically requires event-based data, that is, data about the points in time at which state changes in the system occur (Pidd, 2004). This could involve arrival times, service times, failure times, or other event timings. For example, in a ship recycling context, DES would need data about when ships arrive for recycling, how long each stage of the recycling process takes, and intervals between safety inspections or incidents.

DES offers flexibility in handling complexity. It's especially apt for systems where the sequence of events and their timing are crucial. As it captures these dynamics precisely, it allows detailed insights into system performance and potential areas of improvement. The stochastic nature of DES (random variability in the process) can offer a more realistic representation of many real-world systems where uncertainty and randomness play significant roles (Banks et al., 2009; Pidd, 2004). Also, DES can handle contention for resources effectively - a scenario that often surfaces in ship recycling, where resources like labour, equipment, or space may be constrained.

DES models can be computationally intensive, especially for large systems with a multitude of events and resources. Accurate modelling with DES requires substantial data about event timing, sequence, and associated resources, which may not always be readily available. The DES model's complexity can also increase rapidly with the size of the system, making it more challenging to build and validate the model (Schruben, 2010).

DES is widely applied in various sectors. In healthcare, DES is often used to improve patient flow by identifying bottlenecks and Optimising resource allocation. For example, Williams *et al.* (2020) used DES to model ICU bed capacity and found that reducing transfer delays was more effective than simply adding beds. In manufacturing, it's used for process optimisation, facility planning, and equipment scheduling (Jahangirian et al., 2010). In transportation, DES models can help optimise schedules, manage fleets, and assess policy impacts on traffic flow (Chen, 2010).

6.4 Selection of modelling and simulation techniques for the ship recycling process

In the previous section, we discussed three promising modelling techniques: System Dynamics (SD), Agent-Based Modelling (ABM), and Discrete Event Simulation (DES). Each of these methods has its unique strengths and limitations and is particularly suited for different types of systems and research questions. The selection of the most appropriate modelling technique for a specific research problem involves a comparative analysis of the potential methods. This analysis considers the specific characteristics and requirements of the research problem and assesses how well each method can meet these needs. Thus, a following section will show a systematic approach towards performing this comparative analysis, tailored for the context of ship recycling.

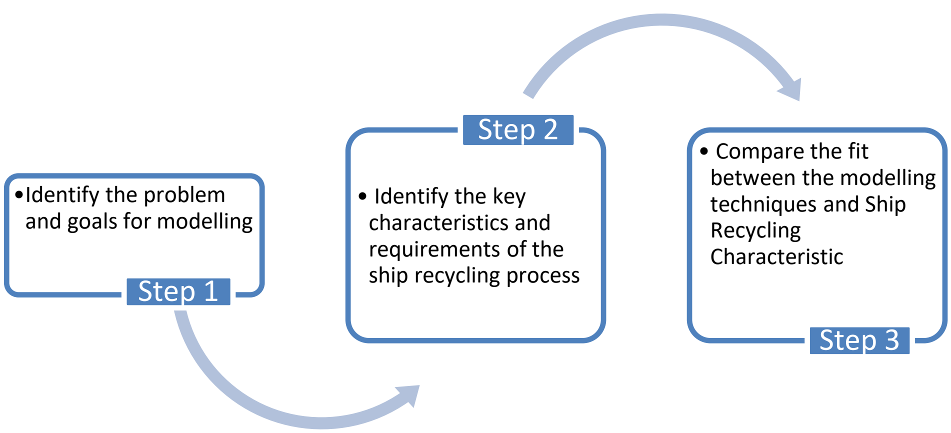


Figure 6. 1: Step-by-step the selection of modelling techniques

6.4.1 Identify the problem and goals for modelling.

In our endeavour to model and improve the ship recycling process, it is essential to first clearly outline the problem we're aiming to solve and the goals we hope to achieve. This ensures a well-directed approach when considering and applying different modelling techniques. To ensure a comprehensive understanding of the complex problem at hand and define our goals clearly, we employ the CATWOE analysis technique. To develop a comprehensive understanding of the complex problem at hand and to define our goals with clarity, we utilise the **CATWOE analysis** technique. Developed by Peter Checkland (1981) as part of his Soft Systems Methodology, CATWOE is a well-established tool in business and systems analysis. It provides a structured framework for examining complex problems from multiple perspectives. The acronym stands for **Customers, Actors, Transformation process, Worldview, Owner,** and **Environmental constraints**, each representing a unique lens through which the problem situation can be explored (Checkland, 1981).

This technique originates from Soft Systems Methodology (SSM), a problem-solving approach that emphasizes understanding the problem context before seeking solutions, promoting a holistic and inclusive view of complex systems (Williams & Hummelbrunner, 2010)2. The application of CATWOE thus helps to structure thoughts, ensuring comprehensive consideration of all relevant aspects, thereby improving decision-making and planning (Bell & Morse, 2013). Thus, below is the application of CATWOE in the context of modelling for ship recycling:

- Customers: Who are the beneficiaries or victims of the ship recycling process? This might include ship owners, ship recyclers, and regulatory bodies, but also broader groups such as local communities affected by recycling activities and global stakeholders in environmental sustainability.
- Actors: Who are the individuals or groups involved in carrying out the process? This might include workers at recycling facilities, but also other entities like logistics providers or waste management companies.
- Transformation Process: What is the process that converts inputs into outputs? In this case, it's the ship recycling process, transforming retired ships into reusable materials and waste.
- Worldview: What's the big picture and what are the broader impacts of the problem? For your study, the worldview might be about the environmental, social, and economic implications of ship recycling.

- Owner: Who owns the process or problem situation and has the power to bring about change? This might be shipping recycling companies, but also entities like governmental bodies or international organisations regulating the process.
- Environmental Constraints: What are the constraints and restrictions that need to be considered? This can include regulatory restrictions, availability and cost of resources, technological limitations, and more.

In this study, we have conducted an in-depth examination of the complex context of ship recycling by interacting with a long number of stakeholders. The application of the CATWOE framework has provided a structured approach to comprehensively capture the dynamics of the ship recycling process from various perspectives. This detailed exploration has allowed us to effectively frame the problem at hand and set our research goals, subsequently guiding our selection and application of modelling techniques.

To provide a holistic view of the problem and gain insights into the ship recycling process, interviews were conducted with six key stakeholders, each representing a different perspective within the CATWOE analysis framework. The stakeholders included a Ship Owner, a Ship Recycling Facility Manager, a Worker at the recycling facility, a Representative from an Environmental Regulatory Body, a Logistics Service Provider, and a Community Leader from a region affected by ship recycling activities.

Table 6. 1: CATWOE Analysis Result

Customer	The Ship Owner, as a customer, emphasized the importance of a predictable and efficient recycling process. An unpredictable process can lead to unforeseen costs and delays, impacting the bottom line.
Actors	Both the Recycling Facility Manager and the Worker had their unique insights. The Facility Manager stressed the need to improve efficiency and reduce waste, whereas the Worker's concerns were primarily around safety and the predictability of workflow.
Transformation Process	The Logistics Service Provider, being part of the transformation process, highlighted the challenges with scheduling and synchronizing activities due to the dynamic nature of the recycling process.

Worldview	The Regulatory Body Representative and the Community Leader provided insights into the broader impacts of ship recycling. The Regulatory Body Representative pointed out the potential environmental hazards of ship recycling and the importance of adhering to environmental standards. The Community Leader, on the other hand, discussed the social implications, including the effect on local employment and the potential for environmental pollution impacting the local community.
Owner	The Facility Manager, besides being an actor, is also the owner of the process, having the power to implement changes at the ground level. They expressed the need for a tool to assist in decision-making and strategy planning.
Environmental Constraints	The Regulatory Body Representative discussed various environmental constraints, including emission standards and waste disposal regulations. The Logistics Service Provider mentioned operational constraints such as the availability of transport and limitations on timings due to noise regulations in the local area.

Based on the insights from these stakeholders, a comprehensive understanding of the challenges and needs associated with the ship recycling process was developed. Thus, the problem statement and goal have been developed as follows.

Problem Statement: After conducting the CATWOE analysis, we can define our problem as follows: The ship recycling process is complex, with varied stakeholders and significant environmental constraints. Identifying and improving inefficiencies in this dynamic process is a challenge that a comprehensive model can address.

Goals: Based on our problem statement and the insights gathered from the stakeholders, our goals for this research are:

- Develop a comprehensive model that accurately captures the ship recycling process, identifying potential bottlenecks and areas for improvement.

- Use the model as a tool for scenario analysis, enabling stakeholders to make informed decisions about improving the process.
- Construct an improved model based on the identified solutions and perform a comparative analysis with the original model to evaluate potential improvements.

These goals align with the needs expressed by our stakeholders, guiding our selection of an appropriate modelling technique. We discuss this selection process in the next section.

6.4.2 Identify the key characteristics and requirements of the ship recycling process.

To identify the key characteristics and requirements of the ship recycling process, a stakeholder analysis was performed. Interacting with stakeholders can provide valuable insights into the process. Stakeholders have unique perspectives and experiences that could reveal specific characteristics or requirements of the ship recycling process that are not immediately apparent. Insights into the different aspects of the process, how they view and interact with it, and what they perceive as its main features, challenges, and opportunities, can be gained. The process of stakeholder analysis can be seen in Figure 6.2 below.

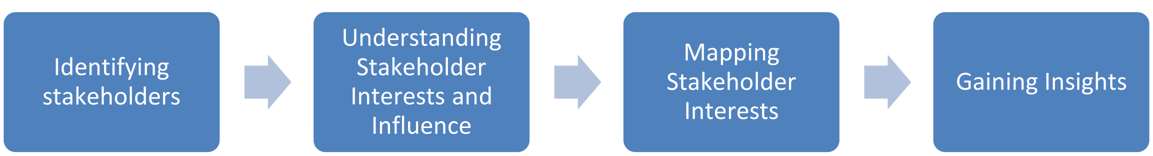


Figure 6. 2: Stakeholder analysis into the modelling process

6.4.2.1 Identifying stakeholders

The identification of stakeholders is the first critical step in the stakeholder analysis process. It involves cataloguing all the individuals, groups, or organisations that have a vested interest in the ship recycling process, either directly or indirectly. A thorough understanding of each stakeholder's role in the recycling process is paramount as it provides the foundation for further analysis.

Table 6. 2: Identified stakeholders in ship recycling

Stakeholders	**Explanation**

Ship Owners	The ship owners, those who possess the vessels to be recycled, represent a vital stakeholder group in this process. Their decisions significantly impact the ship recycling process, including when and where a ship will be recycled, the chosen recycling facility, and their expectation for the cost-effectiveness of the process. Understanding the ship owners' concerns and motivations can provide valuable insights into the economic aspects of ship recycling
Recycling Facility Managers	Facility managers are responsible for overseeing the ship's recycling operations. They make decisions related to the process's execution, resource allocation, compliance with safety and environmental standards, and workers' well-being. Engaging with facility managers can offer a granular view of the on-ground challenges and opportunities in ship recycling.
Ship Recycling Workers	The workforce executing the recycling process plays an indispensable role in ship recycling. Their experiences and perspectives can shed light on the realities of the working conditions, potential safety risks, job satisfaction, and potential areas of process improvement
Regulatory Bodies	Regulatory bodies such as government agencies and international organisations set and enforce guidelines and regulations for ship recycling. Their primary concern is ensuring that ship recycling adheres to safety, environmental, and labour regulations. Their insights can reveal the compliance landscape and its impact on the recycling process.
Local Community Representative	Local communities living near recycling facilities can be significantly impacted by recycling operations. Their views on the social and environmental implications of ship recycling can provide a different yet essential perspective on the broader impact of the ship recycling process
Logistic Services	Logistics service providers, responsible for the transport of materials and waste during and after the recycling process, play an often

	overlooked but crucial role in ship recycling. Their insights can help identify logistical challenges and their solutions within the ship recycling process.
Waste Management Company	Waste management companies handle the disposal or repurposing of waste produced during recycling. Understanding their challenges and concerns can reveal insights into waste management within the ship recycling process, a critical aspect from an environmental perspective

Through comprehensively identifying the various stakeholders involved, this research aims to gather diverse and rich insights into the ship recycling process. This understanding would form the basis for the subsequent stages of the stakeholder analysis and model development.

6.4.2.2 Understanding stakeholder's interests and influence

Understanding the interests and influence of each stakeholder group is a crucial step in stakeholder analysis. Each stakeholder brings their own unique perspectives, concerns, and degree of influence to the ship recycling process. The goal of this step is to capture these diverse viewpoints and understand how each stakeholder can shape the process.

The data for understanding the interests and influence of each stakeholder group were gathered through a combination of semi-structured interviews and questionnaires. This mixed-method approach was chosen to ensure both depth and breadth in the collected data.

The semi-structured interviews involved direct conversations with representatives from each stakeholder group. The nature of these interviews allowed for the exploration of topics beyond predefined questions, leading to richer, more nuanced insights. These interviews, while time-intensive, provided an opportunity to delve into the complexities of the ship recycling process, and the specific challenges and concerns of each stakeholder group.

Complementing the interviews, questionnaires were distributed to a broader segment of each stakeholder group. These questionnaires comprised a set of predefined questions designed to gather information on the key interests and influence of each group in the ship recycling process. The use of questionnaires helped to validate the findings from the interviews and ensured representation from a larger section of each stakeholder group. The combination of interviews and questionnaires ensured that a comprehensive understanding of the interests and influence of each stakeholder group was achieved, laying a strong foundation for the subsequent steps of the stakeholder analysis and model development.

Stakeholder group	Interest	Influence
Ship Owners	Maximizing returns from recycling, choice of the recycling facility, the timing of recycling process	The decision to recycle the ship, choice of recycling facility, timing of the recycling process
Recycling Facility Managers	Efficient operations, compliance with regulations, and maintaining safety standards	Overseeing the recycling operations, ensuring compliance, and maintaining safety protocols
Workers	Safety, job security, working conditions	First-hand knowledge of practical challenges, direct involvement in the recycling process
Regulatory Bodies	Ensuring compliance, minimising negative impacts	Setting and enforcing safety, environmental, and labour standards
Community Representatives	Social and environmental impact of recycling operations	Voicing community concerns, highlighting the broader social and environmental impacts of recycling operations

Logistics Service Providers	Efficient scheduling, cost-effectiveness, minimising the environmental impact of transportation	Impact on overall efficiency of the recycling process through handling of material and waste movement
Waste Management Companies	Effective and compliant waste management, minimising the environmental impact of waste disposal	Handling of waste produced during recycling, influencing environmental sustaina

The insights gained are then organised into a stakeholder map to categorize the stakeholders based on their interests and influence. The stakeholder map serves as a powerful visual tool, allowing a clear understanding of each stakeholder's role and importance in the recycling process, guiding further stages of the analysis and model development.

6.4.2.3 Mapping stakeholder's interests.

Mapping stakeholder interests involves understanding and documenting the objectives, concerns, and motivations of each stakeholder group. This process is crucial to provide a more holistic understanding of the ship recycling system and to ensure that the model created accurately reflects the diverse perspectives involved.

	High Interest	**Low interest**
High Influence	Recycling Facility Managers, Ship Owners Regulatory Bodies,	Waste Management Companies
Low influence	Community Representative, Workers	Logistic services provider

Figure 6. 3: Stakeholder mapping illustration

- **High Influence, High Interest:** This category includes Recycling Facility Managers and Ship Owners. These groups have a significant stake in the ship recycling process and hold a lot of influence over its outcomes. Their objectives and concerns need to be carefully considered and addressed.
- **High Influence, Low Interest:** Regulatory Bodies fall into this category. While they have significant control over the ship recycling process due to their ability to enforce regulations, they might not be directly impacted by the outcomes. Despite their low interest, their influence makes them a crucial stakeholder to consider.
- **Low Influence, High Interest:** This category includes Community Representatives and Workers. While these groups might not have significant control over the ship recycling process, they are directly impacted by its outcomes and hence, have a high interest in the process. Their voices are critical to include to ensure fairness and justice.
- **Low Influence, Low Interest:** This category includes Waste Management Companies and Logistic Service Providers. These groups have a relatively peripheral role in the ship recycling process and may not be heavily impacted by its outcomes. However, their interests still need to be considered, particularly in scenarios where their role might become more significant.

The stakeholder map guided us in identifying and focusing on stakeholders who hold high influence and high interest, such as Recycling Facility Managers and Ship Owners. Their substantial involvement in the system and their capacity to effect change made them a priority for deeper engagement. By understanding their objectives and concerns better, we could anticipate and manage potential obstacles and enlist their cooperation, thereby increasing the likelihood of successful implementation of proposed changes or strategies.

However, while prioritizing high influence and high interest stakeholders, our mapping process also made clear that all stakeholders are integral to the overall functioning of the system. Lower influence or interest stakeholders might not be the primary focus, but their interests and contributions were certainly not overlooked. Including their perspectives not only helped us capture a more comprehensive picture of the system but also ensured that the proposed strategies were equitable and did not disproportionately disadvantage any stakeholder group.

In essence, the stakeholder mapping helped us prioritize and allocate our resources effectively and strategically, ensuring balanced engagement with all stakeholders and Optimising our interventions in the ship recycling system.

6.4.2.4 Gaining Insight

After mapping the stakeholder interests and influence, the next step would be to develop a series of in-depth interview questions that aim to explore these interests and concerns more thoroughly. The responses to these questions can provide detailed insights into the unique perspectives of each stakeholder group and highlight areas of agreement or disagreement among them. The questions should be tailored to each stakeholder group (See appendix 7.1), taking into account their specific roles, concerns, and perspectives related to the ship recycling process. They should be open-ended to encourage detailed responses and allow for follow-up questions based on the participants' answers. The objective of these interviews is not only to gain a more profound understanding of the stakeholders' interests but also to understand the context in which these interests arise. Table 6.3 represents the transcribed responses categorized by stakeholder.

Table 6. 3: Transcribed responses

Stakeholder Group	Transcribed Response	Category
Ship Owners	"The high costs of compliance make recycling less profitable."	Economic Viability
Recycling Facility Managers	"Managing hazardous materials while maintaining profitability is a constant challenge. There's pressure to balance safety and costs."	Health & Safety / Economic Viability
Workers	"We need better protective equipment and training to handle toxic materials safely. Accidents are frequent."	Health & Safety
Regulatory Bodies	"Maintaining high standards while ensuring industry viability is essential. We need more evidence of compliance."	Compliance with Regulations

Community Representatives	"Ship recycling offers jobs but can harm the environment and health if not done responsibly. We need a balance for community welfare."	Community Impact / Environmental Impact
Logistics Service Providers	"Substandard competition isn't an issue; we all have a fair playing field. However, there's a need for better inventory and risk guidance."	Compliance / Economic Viability
Waste Management Companies	"Managing and disposing of hazardous waste is challenging; more stringent guidelines would help."	Environmental Impact / Compliance

This table provides a clear overview of the stakeholder responses and their corresponding categories, allowing for easy identification and analysis of the key themes and concerns expressed by each stakeholder group. The knowledge gained from these interviews will help clarify and elabourate on the key characteristics and requirements of the ship recycling process. This detailed understanding, in turn, will guide the development of a representative and meaningful model of the ship recycling process.

Thus, combining the steps of identifying the problem and goals, mapping and understanding stakeholder interests and influence, and gaining insights from in-depth stakeholder interviews, we can now collate and present the key characteristics and requirements of the ship recycling process.

- **Complexity and Interdependence of Operations**
  The ship recycling process is a complex and multifaceted operation involving various stakeholders. There is a high level of interdependence between the different stages of the process, from the decision of ship owners to decommission a ship, through the dismantling process managed by recycling facilities, to waste management and disposal.
- **Health and Safety Concerns**
  The safety of workers involved in the ship recycling process is a paramount concern, identified by workers, facility managers, and regulatory bodies alike. Hazardous working conditions pose significant risks, including exposure to toxic materials and the danger of

accidents during the dismantling process. Adequate safety measures, training, and equipment are essential.

- **Environmental Impact**

  Ship recycling carries substantial environmental implications, ranging from the release of hazardous substances during dismantling to the challenge of waste disposal. All stakeholders highlighted the importance of environmentally responsible practices, though perspectives on what this entails and how to achieve it varied.

- **Compliance with Regulations**

  Regulatory bodies enforce a set of laws and guidelines that ship recycling processes need to adhere to. The dynamic and evolving nature of these regulations adds another layer of complexity to the process.

- **Economic Viability**

  From the perspective of ship owners, recycling facility managers, and logistics providers, the economic viability of the ship recycling process is a key characteristic. Costs associated with decommissioning, dismantling, waste management, and compliance with regulations all factor into the overall profitability of the process.

- **Community Impact**

  Community representatives highlighted the impact of ship recycling activities on local communities. This includes employment opportunities, environmental implications, and potential health risks. Balancing the economic benefits with potential negative impacts is a critical aspect of the process.

These characteristics and requirements form a robust foundation for the subsequent stages of this study, guiding the development of a representative and meaningful model of the ship recycling process. The next step in this research is to select a suitable modelling technique that can accurately capture these characteristics and facilitate an analysis that addresses the identified problems and goals.

6.4.3. Compare the fit between the modelling techniques and Ship Recycling Characteristic

Given the multifaceted and interconnected nature of the ship recycling process, the Complexity and Interdependence of Operations becomes pivotal characteristic to capture. Accurately modelling the interdependent stages of decommissioning, dismantling, and waste management is integral to understanding the ship recycling process. This aspect is crucial for identifying potential bottlenecks and inefficiencies, paving the way for Optimising the process.

Moreover, the dynamic and evolving nature of regulations governing ship recycling introduces an additional layer of complexity. Compliance with Regulations becomes a significant characteristic because any model that doesn't incorporate regulatory considerations could misrepresent the constraints and pressures faced by stakeholders involved in ship recycling. A model that can keep track of compliance at each detailed stage of the process will offer a realistic representation of the ship recycling process, facilitating more effective decision-making and strategic planning.

While Health and Safety Concerns, Environmental Impact, Economic Viability, and Community Impact are vital aspects of ship recycling, they will be addressed in the subsequent sections of this study using different analytical approaches. This is due to the fact that these aspects require specific methodological considerations that may not be best captured within the system-level view provided by our selected modelling technique. For instance, health and safety concerns necessitate a deep understanding of worker behaviour and safety protocols, environmental impact requires a focused examination of pollution and waste management techniques, and economic viability demands a detailed financial analysis.

Therefore, focusing the modelling stage of the research on the Complexity and Interdependence of Operations and Compliance with Regulations will allow us to construct a robust and realistic model of the ship recycling process, while the remaining characteristics will be addressed comprehensively using complementary techniques in subsequent sections of this study.

Given the focus on the characteristics of Complexity and Interdependence of Operations and Compliance with Regulations for the modelling stage of this research, Table 6.4 shows the comparison of modelling techniques.

Table 6. 4: The Comparison of modelling techniques

Ship Recycling Characteristic	**System Dynamics (SD)**	**Agent-Based Modelling (ABM)**	**Discrete Event Simulation (DES)**

Complexity and Interdependence of Operations	Good at illustrating the high-level interdependencies between different stages.	Excellent at demonstrating the complexity of interactions between different agents within the system.	Superior in representing detailed process stages and their interdependencies.
Compliance with Regulations	Illustrates the effect of policy changes on the system.	Can simulate the behaviours of individual agents in response to regulations.	Can track compliance at each detailed stage of the process.

SD, ABM, and DES each have unique strengths. SD can depict the high-level interdependencies between different stages but lacks the granularity to dive deep into each process. ABM is excellent at demonstrating complex interactions between individual agents but doesn't inherently provide a comprehensive view of the system. DES, however, can offer both an overview of the system and a detailed understanding of each stage of the process. This makes it highly effective for capturing the Complexity and Interdependence of Operations and for tracking Compliance with Regulations at every stage.

Building on the unique strengths of each modelling technique as discussed, the following table provides a more detailed comparison, emphasizing the criteria of capturing Complexity and Interdependence of Operations and Compliance with Regulations in the context of the ship recycling process, which are paramount for this research.

Table 6. 5: A detailed comparison across various criteria

Criteria	**System Dynamics (SD)**	**Agent-Based Modelling (ABM)**	**Discrete Event Simulation (DES)**
Capturing Complexity of Interactions	Medium	High	High

Representing Interdependencies of Operations	Medium	High	High
Modelling the Dynamic Nature of Regulations	High	Medium	High
Compliance Tracking at Each Stage	Low	High	High
Identification of System Bottlenecks	Low	Medium	High
Adaptability to Regulatory Changes	Medium	High	High
Integration with Optimisation Techniques	Medium	Medium	High

- **Capturing Complexity of Interactions:** Both DES and ABM excel in representing the complex interactions among different entities in the system, such as stakeholders in ship recycling. SD provides a high-level view but may not capture the details of such interactions as effectively.
- **Representing Interdependencies of Operations:** DES and ABM, with their focus on individual entities and process stages, are more suitable for representing the interdependence of different operations in ship recycling. SD generally provides a more aggregate view and may not capture these interdependencies in detail.
- **Modelling the Dynamic Nature of Regulations:** All three methods can handle dynamic regulatory changes. However, DES and SD have an edge due to their ability to model the system-level effects of such changes.
- **Compliance Tracking at Each Stage:** DES and ABM stand out in their ability to track compliance at each detailed stage of the ship recycling process. SD usually models compliance at an aggregate level and may not provide detailed tracking.

- **Identification of System Bottlenecks:** The process-oriented nature of DES makes it superior for identifying specific bottlenecks in the system. While SD and ABM can indicate areas of concern, they are not as effective in pinpointing bottlenecks.
- **Adaptability to Regulatory Changes:** Given their entity-centric approach, DES and ABM are well-suited to adapt to regulatory changes. SD, being more aggregate and systemic, may not be as quick to adapt at an entity level.
- **Integration with Optimisation Techniques:** Among the three methods, DES has a proven track record of successful integration with optimisation techniques, providing a clear advantage for improving the efficiency and effectiveness of ship recycling operations.

In conclusion, Discrete Event Simulation (DES) is selected as the most appropriate modelling technique for representing the ship recycling process, given its capacity to handle key complexities and requirements specific to this domain. DES excels in accurately capturing both the complexity and interdependence of operations across various stages of the recycling process, which involves diverse stakeholders and activities. This approach provides a detailed, entity-level view that allows for a granular representation of each stage, thus aligning with the intricate demands of the ship recycling industry.

Additionally, DES facilitates compliance tracking at each stage, addressing regulatory adherence in a way that high-level methods like System Dynamics (SD) might overlook. The approach also enables the identification of bottlenecks within the process, a strength that makes it invaluable for pinpointing specific areas for improvement. This level of detail is particularly beneficial for addressing operational inefficiencies and Optimising processes, as DES integrates seamlessly with various optimisation techniques (Banks et al., 2005).

Moreover, DES has proven adaptable to dynamic regulatory changes, as it can model the system-level impacts while maintaining flexibility at the entity level. This characteristic aligns with the industry's evolving regulatory landscape, where adaptation to new standards is essential. Given its strengths, DES offers a comprehensive framework to effectively simulate and analyse the ship recycling process, meeting the objectives of this research to develop an accurate and meaningful model.

The selection of Discrete Event Simulation (DES) as the primary modelling technique in this chapter establishes a direct connection to the next stage of the research. Chapter 7 builds on the DES model by integrating the simulation outputs with the risk assessment framework developed in Chapter 5. Specifically, the simulation results provide quantitative insights into process performance, such as bottlenecks, delays, and resource utilisation, which are then used to refine and validate the risk control measures. This iterative process ensures that the framework is both data-driven and practical, linking safety and productivity outcomes. Through this integration, the simulation model becomes more than just a performance analysis tool, it actively supports the cost-benefit evaluation of risk mitigation strategies presented in Chapter 7, forming a unified and coherent framework for improving ship recycling operations.

6.6 Sensitivity and Robustness Analysis

To ensure the developed Discrete Event Simulation (DES) model can provide reliable insights, a sensitivity analysis was conducted. This analysis involved systematically varying key input parameters one at a time (One-At-a-Time method) to assess their impact on key performance indicators such as throughput, waiting time, and resource utilisation. The parameters tested included:

- Number of cutting torches
- Number of workers
- Processing time per cutting task
- Ship arrival rate

The results highlighted which factors had the greatest influence on system performance. This helps decision-makers identify where improvements would yield the most significant productivity and safety benefits.

A full validation process, including face validation, statistical validation, and operational validation, is presented in Chapter 8 (Section 8.3.5). This ensures that the model is not only logically correct but also representative of real-world ship recycling operations.

6.7 Chapter Summary

This chapter explored the application of modelling and simulation techniques in the context of the ship recycling process. The focus was on understanding the complexities of the process and ensuring compliance with regulations. The chapter provided an overview of three modelling techniques, highlighting the suitability of Discrete Event Simulation (DES) for capturing the interdependencies and regulatory requirements of ship recycling. By selecting DES as the modelling technique, the chapter established a solid foundation for further analysis and optimisation.

Chapter 7. Risk-Based Ship Recycling Yard Improvement Framework

7.1 Chapter Overview

This chapter builds directly on the modelling and simulation work presented in Chapter 6, forming the next stage of the integrated framework for improving ship recycling yards. The Discrete Event Simulation (DES) model developed in the previous chapter provides quantitative performance data, such as throughput, delays, and bottlenecks that are used here to refine the risk assessment process. By incorporating these simulation outputs, the framework ensures that hazard identification and risk analysis are grounded in realistic operational conditions rather than theoretical assumptions.

The chapter introduces the first part of the integrated framework, which combines risk management and productivity enhancement. The process begins with the systematic identification of hazards associated with ship recycling activities, followed by a structured risk assessment and quantification to evaluate their significance. Based on this analysis, multiple risk control options are identified and assessed. The cost-benefit analysis stage integrates both the direct safety benefits and the operational improvements measured through the simulation model, enabling evidence-based decisions about which interventions to prioritise.

Through linking safety and productivity outcomes, this chapter demonstrates how risk assessment and simulation interact iteratively, laying the foundation for the final validation and application of the framework in Chapter 8.

7.2 Framework Development

This framework is designed to integrate risk management with productivity improvement, specifically tailored for the ship recycling sector. By applying this framework, ship recycling stakeholders can simultaneously address safety concerns and ensure compliance with regulatory standards. The development of the framework is outlined in the following subsections.

7.2.1 Step 1: Conduct Field Study and Yard Visit

The Primary data collection through field studies forms the foundation for developing the discrete event simulation model. These studies are conducted to gather comprehensive and accurate information, including:

- The overall process flow of ship recycling operations
- Detailed ship recycling procedures, including prerequisites and the spatial layout of processes and activities
- Types and quantities of resources involved in each process
- Process durations and task timings, obtained through in-depth time-motion studies

In addition, identification of detailed job tasks and their hazards are also performed. The data collection form is referred to in Appendix 7

7.2.2 Step 2: Hazard Identification

The purpose of hazard identification is to systematically compile a list of potential hazards and related scenarios, ranked according to their associated risk levels within the context of ship recycling operations. This step is explicitly designed to support a structured and data-driven approach for recognising risks that could result in accidents or other safety incidents.

The core methodology relies on expert input and existing data to identify hazards, assess their root causes, and understand their potential consequences. A structured workgroup approach is employed, wherein experts from relevant disciplines evaluate each phase of the recycling process. This helps to determine causal relationships between activities and potential hazards. The inclusion of multidisciplinary expertise enhances the robustness and accuracy of hazard detection and risk analysis.

Through analysing ship recycling tasks based on job roles and responsibilities, this method ensures that hazard identification is both detailed and context specific. The process incorporates not only the detection of hazards but also the evaluation of their severity and likelihood, forming the foundation for effective risk management strategies.

This study adopts the Failure Mode and Effects Analysis (FMEA) technique, which divides the hazard identification process into a series of discrete steps. The approach used is summarised in Figure 7.1 below.

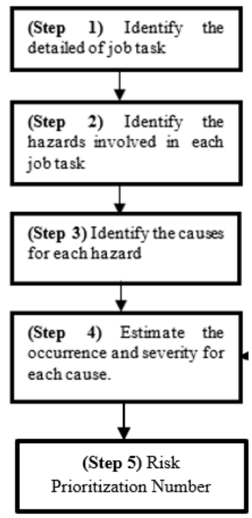


Figure 7. 1: Methodology of Integration of FMEA into risk assessment tool

The process begins by identifying and categorising job tasks (Step 1), which are organised into six distinct activity zones typically found in ship recycling yards:

- Pre-recycling zone
- Primary cutting zone
- Secondary cutting zone
- Storage area
- Waste disposal facilities
- Office buildings and emergency facilities

Based on this classification, Step 2 involves identifying the specific hazards associated with each job task and determining their root causes. This is informed by a curated list of common hazards encountered in ship recycling, which was developed through field observations and expert consultations.

In Step 3, representative examples of hazardous occupational responsibilities are compiled to support the risk assessment team in recognising dangerous scenarios. This enables a more systematic and contextualised evaluation of workplace hazards.

By supplying the assessment team with detailed hazard profiles, including causes, associated tasks, and risk factors, it becomes possible to:

- Systematically analyse and prioritise all potential hazards
- Estimate the severity and likelihood of occurrence (Step 4)

- Enhance team awareness of hazards not previously considered

The overall methodology is grounded in the integration of Failure Mode and Effects Analysis (FMEA), which subdivides the process into structured phases. As illustrated in Figure 7.1, the combination of expert input supports the accurate ranking of hazards and informs targeted risk control strategies.

7.2.2.1 Identify the detailed task.

The first stage involves identifying the specific work activities that require evaluation. In this framework, ship recycling operations are categorised into six main activity zones: pre-recycling, primary cutting zone, secondary cutting zone, storage area, waste disposal facilities (including landfills), office buildings (including administrative offices), and emergency facilities (including fire stations).

This categorisation aims to enhance the clarity, focus, and structure of the evaluation process. While Appendix 3 provides suggested job task lists for each zone, along with supplementary information, users are encouraged to adapt and expand the task lists based on their specific operational contexts. Additional job duties or activities relevant to the actual working environment may be included for further analysis, with reference to the guidance provided in the appendix.

7.2.2.2 Identify the hazards involved in each job task and causes for each hazard

Identifying hazards was the next critical component of this newly proposed method for ship recycling. Workers in the ship recycling industry are exposed to a wide range of risks. These hazards can vary from the more visible and immediately dangerous, such as falling from heights or being struck by falling objects to less visible but equally serious risks, such as prolonged exposure to asbestos fibres.

Observations and feedback from health and safety personnel highlighted that the sheer number and variety of hazards in ship recycling made it difficult to systematically assess and mitigate them without a structured approach. Additionally, it became apparent that some of the less obvious hazards were often overlooked by those responsible for safety, further underscoring the need for a comprehensive and standardised method.

To address this gap, an extensive list of potential hazards was compiled to serve as a reference for ship recycling personnel during task execution. While several organisations have made significant efforts to document hazards in this sector, the list developed by the International Labour Organization (ILO) as part of its Three-Step Method was selected as the foundational reference. This method was later adapted and enhanced for the purposes of this study.

To provide greater context and support to the risk assessment team, additional causal risk factors were incorporated from multiple authoritative sources. These included *Safety and Health in Shipbreaking: Guidelines for Asian Countries and Turkey* (ILO), the *Occupational Safety and Health Manual for Ship Recycling Workers in Bangladesh* (ILO and the Ministry of Labour and Employment, Bangladesh), and the *SAFEREC Project (2003–2007)* led by the United Nations Development Programme (UNDP).

Moreover, illustrative examples of hazardous occupational responsibilities were developed to support the risk assessment team in recognising potentially dangerous scenarios. These examples were informed by extensive field observations and were categorised according to specific operational zones within ship recycling yards. Subcategories were created to reflect more detailed aspects of the work environment.

Through providing the risk assessment team with a comprehensive reference, comprising hazard listings (as detailed in Appendix 7.3), associated risk factors, and representative hazardous job duties, this method enables a systematic evaluation of all possible hazards. It also serves an educational function by raising awareness of less apparent risks that may otherwise go unrecognised.

7.2.2.3 Estimating the occurrence and severity for each cause.

After identifying hazards and their potential causes, the next step involves evaluating the likelihood of each hazard occurring and the severity of its possible consequences. This estimation process is essential for prioritising risks and guiding the selection of appropriate control measures. In ship recycling environments, where quantitative data are often scarce and expert input is crucial, a structured and transparent qualitative approach is required.

To standardise the evaluation, this study adopts linguistic variables to represent both the probability of occurrence and the degree of severity. These descriptors enable consistent scoring across hazard scenarios while remaining intuitive for expert participants.

To ensure fairness and reduce bias in aggregating expert opinions, a multi-criteria decision-making (MCDM) technique is used to weight expert inputs. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was chosen for this purpose. TOPSIS is widely used in risk assessment and safety analysis because of its ability to handle both qualitative and quantitative criteria and to produce a clear ranking of alternatives based on their proximity to an ideal solution. Compared to other MCDM methods such as the Analytic Hierarchy Process (AHP) or ELECTRE, TOPSIS is less complex, requires fewer pairwise comparisons, and is computationally efficient. Its suitability for situations where expert judgment varies across multiple weighted criteria makes it particularly appropriate for this study. Thus, TOPSIS provides a reliable foundation for determining the relative importance of expert contributions in the overall risk assessment process.

Furthermore, the estimation process is carried out through a step-by-step approach, beginning with the definition of linguistic variables, followed by scoring occurrence and severity, and concluding with expert weighting and ranking. Each of these steps is described in detail in the following subsections.

1. Defining linguistic variable

Based on previous research, linguistic expressions are used to describe the input parameters of failure probability and severity (Kurt, 2016) In this study, the likelihood of failure is categorised using the following linguistic terms and corresponding scores: Frequent = 10, Quite Frequent = 7, Unusual = 4, Unlikely = 2, and Extremely Unlikely = 1.
Assessing severity is more complex, as it must account for potential harm to people, environmental damage, and economic losses. To simplify the evaluation, this study adopts a severity classification focused on workforce impact, with a numerical scale from 1 to 10. The scale ranges from no injuries (1), first-aid cases, up to four minor injuries, more than six injuries or disabilities, fewer than nine casualties, to ten or more fatalities (10).This qualitative method is aligned with the approach developed by the U.S. Department of Défense (SESD, 1980), which categorises failure probability into five levels, from frequent to highly improbable (Kurt, 2016). These levels are presented in Table 7.1.

Table 7. 1: Qualitative approach for the levels of probability of the hazard impact Adapted from Santos (2006)

Degree of Frequency	**Rating**
Very frequent, once a day	5
Frequent, once per week or more	4
Quite frequent, once per month	3
Quite unusual, once a year	2
Unlikely, once per 10 years	1
Extremely unlikely, once per 100 years	0

The severity ratings are also categorised using qualitative descriptions. Table 7.2 presents six degrees of severity based on the methodology described by

Table 7. 2: Qualitative approach for the levels of severity of the hazard impact, adapted from Kurt (2016)

People (Workers)	**Rating**
Death or several deaths	5
Disability	4
Longer reporting sick >14d	3
Shorter reporting sick <14d	2
Injury without reporting sick	1
Negligible or harmless injury	0

In addition, the risk matrix used for mapping these values is shown in Figure 7.2.

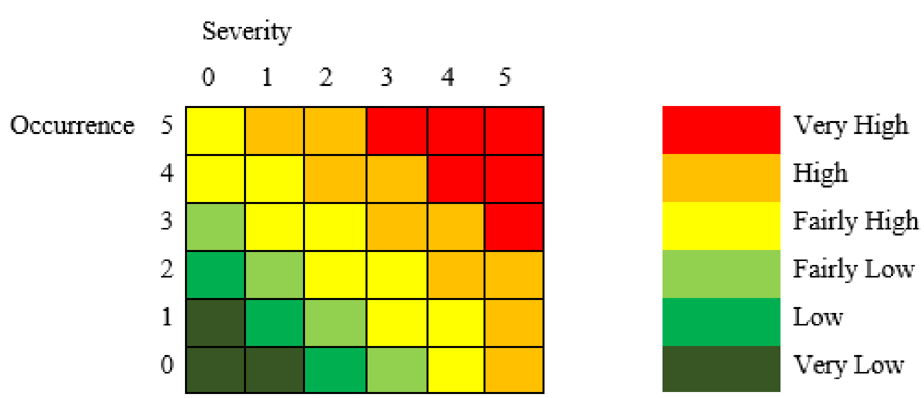


Figure 7. 2: The risk matrix

2. Scoring occurrence and severity

The evaluation was conducted using a structured questionnaire consisting of three main sections. The first section asked participants to select a specific job task. The second section involved identifying hazards and their sources. The third section required respondents to assign scores for the likelihood and severity of each hazard, based on their expert judgment.

3. Expert knowledge elicitation and weighting

Collecting accurate data on maritime operations remains a complex and evolving challenge. Hence, expert judgment becomes indispensable for addressing such limitations when empirical data are incomplete or unreliable (Goerlandt, Khakzad and Reniers, 2017). For this study, experts with relevant experience in ship recycling were selected to provide their input. These experts were asked to evaluate initiating events, estimate the probability of system failures, and assess the potential consequences.

An expert (denoted as E) is defined as an individual with substantial knowledge and familiarity with the system being evaluated. In some cases, different experts may provide different values for the same event. To reduce potential bias, a weighting system was introduced to reflect the relative importance of each participant's input.

The weighting process considered three main parameters: years of experience, sector of occupation, and level of education. Based on the importance assigned a priori, the parameters were weighted as follows:

- Years of experience: 0.40
- Sector of occupation: 0.35
- Level of education: 0.25

Each participant was then ranked using the TOPSIS method, as summarised in Table 7.3.

Table 7. 3: TOPSIS ranking

	Parameter 1	**Parameter 2**	**Parameter 3**
Participant	Wp1	Wp2	Wp3
A1	x1 1	x1 2	x1 3
A2	x2 2	x2 2	x2 3
⋮	⋮	⋮	⋮

A7	X7 1	X7 2	X7 3

Where **Wp1**, **Wp2**, and **Wp3** represent the weights for each parameter. Parameters 1, 2, and 3 correspond to years of experience, sector of occupation, and level of education, respectively.

7.2.3 Step 3: Risk Analysis

The risk analysis stage involves a more detailed examination of the causes, initiating events, and potential consequences associated with the most critical accident scenarios identified during the hazard identification process. This stage may be supported by suitable risk modelling techniques to enhance the accuracy and depth of the analysis.

The primary objective of this step is to focus attention on high-risk areas, allowing the key factors that influence risk levels to be systematically identified and assessed. Hazards should be analysed according to their nature, whether they pose risks to human safety, the environment, or property, to ensure that appropriate mitigation strategies are developed.

An overview of the integrated framework used for this process is presented in Figure 7.3.

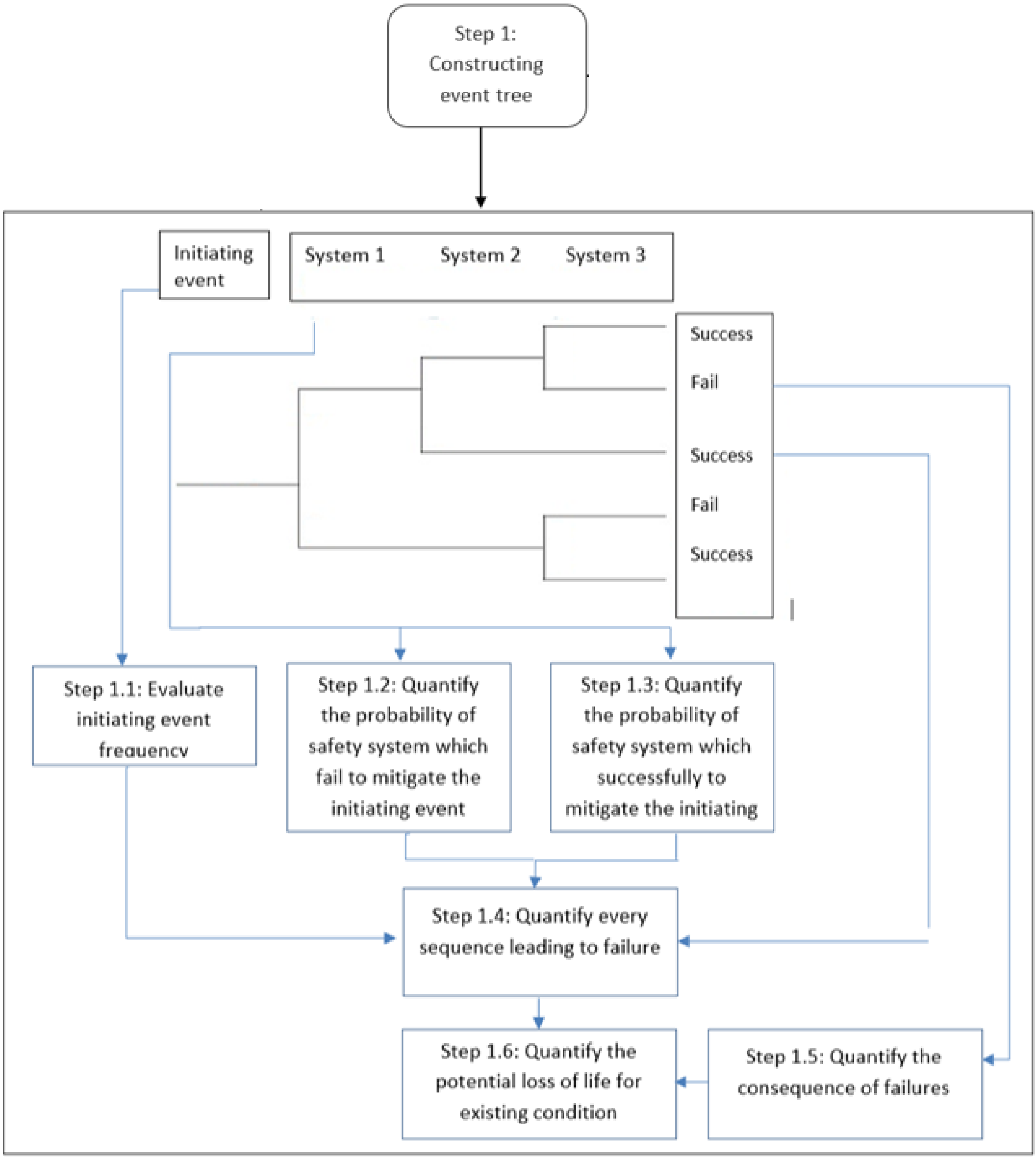


Figure 7. 3: Flowchart of potential loss of life calculation

This stage identifies areas where the human element provides a significant risk to system safety and evaluates the factors that influence the risk level. Event Tree Analysis was used to get this data. An event tree is a type of logic diagram used to investigate the consequences of an accident, a failure, or an unplanned occurrence. The figure depicts the likelihood or frequency of an accident about the safety activities that must be implemented following the occurrence of the event in order to mitigate or avoid escalation. The ET logic diagram is produced first, with the starting event and associated safety system, and then the scenario is constructed to demonstrate the safety system's failure. Additionally, a complete step-by-step may be seen below.

7.2.3.1. Evaluate initiating event frequency

The purpose of this stage is to elicit a failure possibility (1), which indicates the likelihood of the starting event occurring, from a group of experts identified in Table 8.4. In accordance with (2)

$P=\{Pij \mid i=1, 2, \ldots, n; j= 1, 2 \ldots, 7\}$ (1)

$E= \{ei \mid i= 1, 2, 3, \ldots, n\}$ (2)

A failure potential is a qualitative linguistic phrase that refers to the chance of an event occurring. Meanwhile, the genuine value was determined by a crisp number likelihood. Table 7.4 lists seven possible failure modes and their corresponding numbers (Kurt et al., 2016).

The Appendix contains a questionnaire template for collecting data for assessing the beginning event.

Table 7. 4: A set of linguistic failure possibilities and its possibilities value in a year

Failure frequency (H)	**Value in crisp number (n)**
H1= Very frequent	once a day (365 in a year)
H2= Frequent, once per week	52
H3= Somewhat frequent once per month	12
H4= Somewhat unlikely, once a year	1
H5= Unlikely, once per 10 years	0.1
H6= Very unlikely, once per 100 years	00.1

By considering expert justification weights, the output of this step is a yearly frequency of initiating event ($P_{IE}(x)$), which is aggregated from the crisp number in

Step **3: Questionnaire for the expert**

Event No.	Failure Possibilities	Consequence
(2) S1. Success		
(3) S1 Success, S2 Success		
(5) S1 Success, S2 Success, S3 Success		
(8) S1 Fail, S2 Success		
(10) S1 Fail, S2 Success, S3 Success		

Table 1 as shown in (3).

$$P_{IE}(\text{Wilcox \& Ayyub}) = \sum_{i=1}^{n}(wi \times Pij) \qquad (3)$$

Where i represents the i^{th} expert and j represents the j^{th} crisp number.

7.2.3.2 Quantify the probability of safety system which fail to mitigate the initiating event

The goal of this stage is to calculate the probability of all safety systems that will be used in the mitigation scenario. The group of safety systems involved can be represented as follows: (4).

$$SS = \{ssi \mid i = 1,2\ ,\ \dots,\ n\} \qquad (4)$$

Where *ssi* is the i^{th} safety system, and n is the number of involved safety systems. Given that the paths via an event tree are created in binary trees to signify a system's success or failure, this step generates two types of crisp probabilities. The first set is a collection of discrete probabilities that describe the chance of the safety systems failing to operate correctly. The second set is a discrete probability expressing the probability that the safety systems will operate correctly.

The first set is derived by analysing and quantifying the failure scenario of the target safety system using language concepts that have been transformed to crisp, as shown in Table 7.5. The questionnaire template for collecting data to estimate the chance of a safety system failing to mitigate the initial event is included in the appendix.

Table 7. 5: A set of failure probability linguistic and crisp number

Failure probability	Score	Crisp
Very low	1	0.125
Low	2	0.25
Reasonably low	3	0.375
Moderate	4	0.5
Reasonably High	5	0.625
High	6	0.7
Very High	7	0.875

The group of failure probabilities indicating the possibility that the safety mechanisms in (4) will fail to operate properly can be represented as in (5).

$Pssf = \{Pssif \mid i= 1,2, \ldots, n\}$ (5)

Where *sif* means that ssi fails to function.

The second set of failure probabilities representing the success of the safety systems in (4) to function can be denoted as in (14).

$Psss = \{Pssis \mid i= 1,2, \ldots, n\}$ (6)

where subscript s in ssis means that ssi is successfully to function. *Pssis* (Wilcox & Ayyub) in (6) is quantified from corresponding Pssf (Wilcox & Ayyub) in (5) as denoted in (7)

$Pssis = 1- Pssif$ (7)

7.2.3.3 Quantify every sequence leading to failure

The objective of this step is to generate a set of event sequences whose consequence is failure damage (FD) as denoted in (8)

$FD = \{fdi \mid i=1, 2, \ldots, m\}$ (8)

where cdi denotes the ith event sequence and m denotes the total number of events resulting to failure damage. A sequence of events begins with an initiating event and continues with a series of functional safety systems (ssis) and/or failing safety systems (ssif). Additionally, every event sequence fdi in (8) could be indicated by the notation in (9).

$Fdi = \{IE, ss1s/f, ss2s/f, ss3s/f, \ldots ssns/f\}$ (9)

where IE is the initiating event, ssi is the ith safety system, n is the number of safety systems in (4), and subscript s/f in ss1s/f means success or fail.

7.2.3.4 Quantify the consequence of failures

The calculation of consequence of each failure which is the probability of death, using the linguistic terms which converted into crisp as seen in the below.Where *ssi* is the *ith* safety system, and n is the number of involved safety systems. Given that the paths via an event tree are created in binary trees to signify a system's success or failure, this step generates two types of crisp probabilities. The first set is a collection of discrete probabilities that describe the chance of the safety systems failing to operate correctly. The second set is a discrete probability expressing the probability that the safety systems will operate correctly.

The first set is derived by analysing and quantifying the failure scenario of the target safety system using language concepts that have been transformed to crisp, as shown in Table 7.5. The questionnaire template for collecting data to estimate the chance of a safety system failing to mitigate the initial event is included in the appendix.

Table 7. 6: Degree of severity

Degree of severity	**Score**	**Crisp**
Very low	1	0.125
Low	2	0.25
Reasonably low	3	0.375
Moderate	4	0.5
Reasonably High	5	0.625

High	6	0.7
Very High	7	0.875

5. Quantify the potential loss of life for existing condition

Calculation of each failure's potential loss of life (PLL) based on the frequency and severity of accidents by multiplying (9) and (10). At the end, total potential loss of live can be donated in (11)

$$PLL = \sum_{i=1}^{n} (fdi \times ci) \qquad (11)$$

7.2.4 Step 4: Risk Control Options

The objective is to identify Risk Control Measures (RCMs) and then arrange them into a small number of Risk Control Choices (RCOs) that may be used as realistic regulatory options. This phase will consist of the following four stages:

1. Concentrating on risk areas that require control
2. Identifying prospective RCMs
3. Assessing the success of the RCMs in decreasing risk through a re-evaluation of risk analysis
4. Classifying RCMs into possible regulatory choices

This stage tries to provide alternative risk management that meets both current and those created by new technology or operating and management practices. Consider both historical hazards and newly detected risks (from stages 1 and 2), resulting in diverse risk control strategies. Techniques should be employed that address both particular dangers and underlying causes. Step 4 examines how the human aspect is included in examining technological, human, work environment, personnel, and management-related risk control alternatives.

Controlling hazards connected with human contact with a system is similar to developing other risk control strategies. Specific measures can be provided to.1 lessen the frequency of failure; mitigate the impacts of failure;3 relieve the conditions under which failures occur; and.4 reduce the consequences of accidents.

7.2.5 Step 5: Perform Cost-Benefit Assessment

The objective of the Cost-Benefit Analysis is to identify and analyse the advantages and costs of implementing each RCO identified and described in the preceding stage. The following phases may be included in the cost-benefit analysis: .1 take into account the risks evaluated, both in terms of frequency and consequence, in order to determine the base case in terms of the situation's risk levels; 2 organize the RCOs described in step 3 in a way that facilitates comprehension of the costs and benefits associated with their adoption; 3 calculate the associated costs and benefits for each RCO. 4 calculate and evaluate the cost-effectiveness of each option in terms of cost per unit risk reduction by dividing the net cost by the risk reduction obtained as a consequence of adopting the option; and. Five ranks the RCOs to assist the decision-making recommendations in step 5 (e.g., to screen those that are not cost-effective or impractical). Several indices exist to quantify cost-effectiveness related to life safety, such as the Gross Cost of Averting a Fatality (Gross CAF) and the Net Cost of Averting a Fatality (Net CAF).

7.2.5.1 Gros Cost of Averting a Fatality (GCAF)

GCAF is cost-effectiveness measure in terms of ratio of marginal (additional) cost of the risk control option to the reduction in risk to personnel in terms of the fatalities averted, i.e.

$$GCAF = \frac{\Delta Cost}{\Delta Risk}$$

ΔCost is all the cost involved in order to operate the risk control such as: purchasing cost, operational cost, training cost, maintenance cost, operator cost, as denoted below.

$\Delta Cost = PV_0 + FV_0\, x\, (\frac{1-(1+i)^{-n}}{i})$, where:

PV_0: Capital cost

FV_0: Annual maintenance and operation cost

i: Interest rate

n: expected operational life of RCO

ΔRisk is the fatality averted (potential lost of life that can be saved) which can be estimated from:

1. Observation of the Willingness-To-Pay to avert a fatality.

2. Observation of past decisions and the costs involved with them
3. Consideration of societal indicators such as the Life Quality Index (LQI)

For this framework, the proposed values for NCAF and GCAF in table below were derived by considering societal indicators (refer to document MSC 72/16, UNDP 1990, Lind 1996).

Table 7. 7: Criteria of NCAF and GCAF

	NCAF (US $)	GCAF (US $)
Criterion covering risk of fatality, injuries and ill health	3 million	3 million
Criterion covering only risk of fatality	1.5 million	1.5 million
Criterion covering only risk of injuries and ill health	1.5 million	1.5 million

7.2.5.2 Net Cost of Averting a Fatality (NCAF)

A cost-effectiveness ratio expressed in terms of marginal (extra) cost, which accounts for the economic advantages of the risk control option relative to the decrease in risk to personnel expressed in terms of prevented deaths, i.e.

$$NCAF = \frac{\Delta Cost - \Delta Economic\ Benefit}{\Delta Risk}$$

In this framework, the economic benefit can be calculated from the efficiency assessment as shown in the framework below.

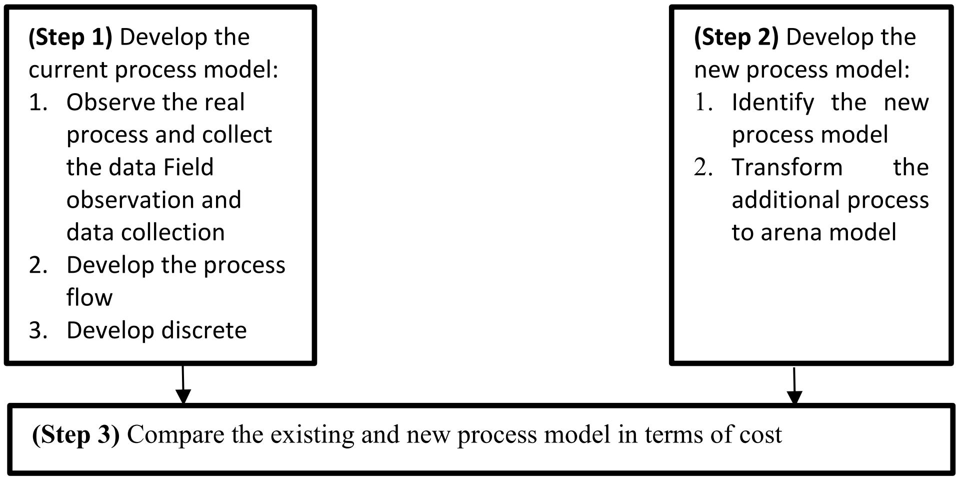


Figure 7. 4: Methodology for improvement process model in ship recycling yard using discrete event simulation and expert judgment in terms of efficiency.

Furthermore, an in-depth explanation of this framework, including its underlying principles, structure, and application, will be thoroughly discussed in Chapter 8. The next chapter builds directly on the findings presented here by demonstrating how the risk control options identified through the cost-effectiveness calculations are tested and validated using the Discrete Event Simulation (DES) model developed in Chapter 6.

This iterative process ensures that:

1. The risk assessment results inform the simulation design and parameters.
2. The simulation outputs, such as efficiency gains and bottlenecks removed, feed back into the cost-benefit evaluation to verify the effectiveness of proposed improvements.

Through integrating risk and productivity considerations in this way, Chapter 8 provides a comprehensive view of how safety interventions can be optimised not only to save lives but also to enhance operational performance in ship recycling yards. This closes the loop of the integrated framework, ensuring evidence-based decision-making for sustainable and safe ship recycling operations.

7.3 Chapter Summary

This chapter presented the Risk-Based Ship Recycling Yard Improvement Framework, an integrated approach designed to enhance both safety and productivity within ship recycling operations. The chapter detailed the development of the framework through a series of structured steps, beginning with field studies for data collection, hazard identification and screening, estimation of potential loss of life, and assessment of risk control options through cost-benefit analysis. Each stage aims to support informed decision-making by identifying high-risk areas and evaluating the effectiveness of potential interventions. The next chapter will focus on the discrete event simulation component developed using ARENA software, which forms a key element of the cost-benefit analysis within the overall framework.

Chapter 8. Employing Discrete Event Simulation and Optimisation in a Cost-Benefit Analysis Framework

8.1 Chapter Overview

This chapter builds directly on the risk-based framework and cost-benefit methodology developed in Chapter 7 and the Discrete Event Simulation (DES) model designed in Chapter 6. It represents the final stage of the integrated framework, where simulation and risk assessment are fully combined to provide an evidence-based approach for improving ship recycling yard operations.

Here, DES is applied using ARENA software to test the risk control options (RCOs) identified in Chapter 7. By simulating different scenarios, the model generates quantitative data on process efficiency, bottlenecks, and resource utilisation. These simulation outputs are then fed back into the cost-benefit calculations, allowing for a robust evaluation of each RCO in terms of both safety improvements and operational performance gains.

The primary objective of this chapter is to demonstrate how this iterative process closes the loop between risk management and productivity optimisation. This integration provides a comprehensive decision-making tool for stakeholders, supporting not only the reduction of accidents and fatalities but also the development of safer, more efficient, and sustainable ship recycling practices.

8.2 An Overview of Cost-Benefit Analysis

Cost-Benefit Analysis (CBA) is a strategic decision-making tool that is extensively used in economic evaluation and project appraisal. It offers a systematic approach to weighing the pros and cons of a decision or project, by quantifying and comparing the costs and benefits associated with it. The primary objective of CBA is to assist in making economically sound decisions, promoting efficient allocation of resources.

8.2.1 Fundamentals of Cost-Benefit Analysis

The essence of a CBA lies in its ability to put a monetary value on all costs and benefits related to a project or decision, enabling its net benefit or worth to be calculated. Costs generally refer to any direct expenditures such as equipment, materials, labour, or time. They also include indirect or opportunity costs, representing alternatives foregone due to the implementation of the project or decision.

Benefits, on the other hand, refer to the gains resulting from the project or decision. These gains could be direct, such as revenue or savings, or indirect, like improved customer satisfaction, increased productivity, or enhanced reputation. Assigning monetary value to these benefits, particularly the indirect ones, can be challenging but is crucial for a comprehensive analysis.

In CBA, it is also essential to account for the time value of money, which recognizes that a dollar today is worth more than a dollar in the future. To achieve this, techniques like Net Present Value (NPV) or Discounted Cash Flow (DCF) are employed.

8.2.2 Application of Cost-Benefit Analysis in System Evaluation

In system evaluation, CBA plays a critical role in examining the economic feasibility of different system designs, modifications, or strategies. It aids in understanding the financial implications of implementing various system configurations and their expected benefits. This includes evaluating the cost of resources required for system implementation, operation, and maintenance, and the benefits derived from system efficiency, risk reduction, increased productivity, and other performance enhancements.

By providing a comparative analysis of costs and benefits, CBA assists in selecting the most economically viable and beneficial system options. Consequently, it ensures that the system delivers maximum value for the resources invested and aids in making informed economically justified decisions. Importantly, these evaluations can be significantly enhanced by utilising simulation techniques, as mentioned in the previous chapter.

When combined with discrete event simulation, such as ARENA software, CBA becomes an even more powerful tool for system evaluation. Simulation allows for complex system behaviours and interactions to be modelled and observed over time. This can provide detailed insights into potential costs and benefits under various scenarios, enhancing the accuracy of the CBA.

This advanced level of analysis facilitates a deeper understanding of system dynamics and the potential impacts of different decisions, leading to more reliable and effective system design and implementation strategies. The next sub-section will further elaborate on the concept and application of discrete event simulation using ARENA software.

In this framework, following the crafting of risk control strategies as mentioned in the previous chapter, the objective of CBA is to evaluate the costs and benefits associated with each of the identified Risk Control Options (RCOs) from the previous step. By undertaking this analysis, we ensure that our proposed safety measures are not just effective but also economically viable.

- Consider the Evaluated Risks: The first step in our CBA is to reflect upon the risks that have been evaluated in terms of their frequency and consequences. This establishes a base case scenario reflecting the current risk levels, which then serves as a benchmark for further comparisons.
- Arrange the RCOs: Next, we organize the proposed RCOs in a manner that simplifies understanding the costs and benefits associated with each. This systematic presentation facilitates a more straightforward comparison and evaluation of the RCOs.
- Calculate Costs and Benefits: Each RCO comes with its own set of implementation costs and potential benefits in terms of risk reduction. By quantifying these for each option, we can clearly assess the economic feasibility of the proposed controls.
- Determine Cost-Effectiveness: This involves evaluating the cost-effectiveness of each option by calculating the cost per unit of risk reduction. Essentially, it entails dividing the net cost of implementing an RCO by the amount of risk reduction achieved as a result.
- Rank the RCOs: The final step in our CBA is to rank the RCOs based on their cost-effectiveness. This ranking aids in decision-making, by helping identify those options that offer the best value in terms of risk reduction per unit cost, and potentially eliminating those that are not cost-effective or impractical.

Several metrics can be employed to quantify cost-effectiveness with respect to life safety. Notable examples include the Gross Cost of Averting a Fatality (Gross CAF) and the Net Cost of Averting a Fatality (Net CAF). These indicators help us to better understand the economic implications of our safety interventions, contributing to a more holistic and informed approach to risk management in the ship recycling industry.

8.3 Discrete Event Simulation: Utilising ARENA Software

The utilisation of discrete event simulation with ARENA software (Sefer Anil Gunbeyaz, Kurt, & Turan, 2018; S. A. Gunbeyaz, Kurt, & Turan, 2020) allowed for a thorough analysis of ship recycling yards to enhance their efficiency and optimise procedures, thereby achieving cost-effective facilities. This study aims to increase productivity and streamline operations within ship recycling yards.

ARENA software has been successfully employed in various fields, including traffic management simulations for unsignalized T-junctions during peak hours (Kamrani et al., 2014). It has also been utilised to improve the Hold Baggage Security Screening system at Kuwait International Airport (AlKheder, Alomar, & Aladwani). Furthermore, ARENA, in conjunction with discrete event simulation, has been applied to shipyard studies, ranging from yard design to resource optimisation, to increase throughput, reduce costs, and enhance resource utilisation (Goo, Chung, & Han, 2019; Ozkok, 2012)

Given the proven capabilities of ARENA software, discrete event simulation using ARENA was chosen as the methodology for this research. The study focused on a traditional Indonesian ship recycling yard, an industry with the potential for significant development on a national and global scale (Fariya et al., 2016). By applying discrete event simulation with ARENA, we were able to analyse the existing ship recycling activities in Indonesia, considering their impact on worker safety, environmental concerns, and public health risks associated with food chain contamination.

The simulation model developed in this study provides a valuable tool for evaluating and Optimising ship recycling yard operations, aiming to improve efficiency, reduce risks, and contribute to the sustainable growth of the ship recycling industry.

8.3.1 Identifying Relevant Modules in ARENA

In the simulation process using ARENA, it is essential to identify the relevant modules that contribute to the effectiveness of the simulation. These modules are designed to handle various aspects of the system being simulated and enable a comprehensive evaluation of its performance.

The interconnected elements in an ARENA simulation include entities, resources, attributes, variables, and controls. Entities represent the objects or components within the system, while resources are the assets or factors required for the system's operation. Attributes define the characteristics or properties of the entities, and variables capture the changing aspects of the simulation. Controls govern the flow and behaviour of the entities and resources within the system.

To ensure accurate and reliable simulation results, data fitting plays a critical role. The Input Analyser tool in ARENA assists in this process by providing statistical analysis and fitting techniques (Figure 8.1). It helps match the collected data with appropriate probability distributions, enhancing the accuracy of the simulation model.

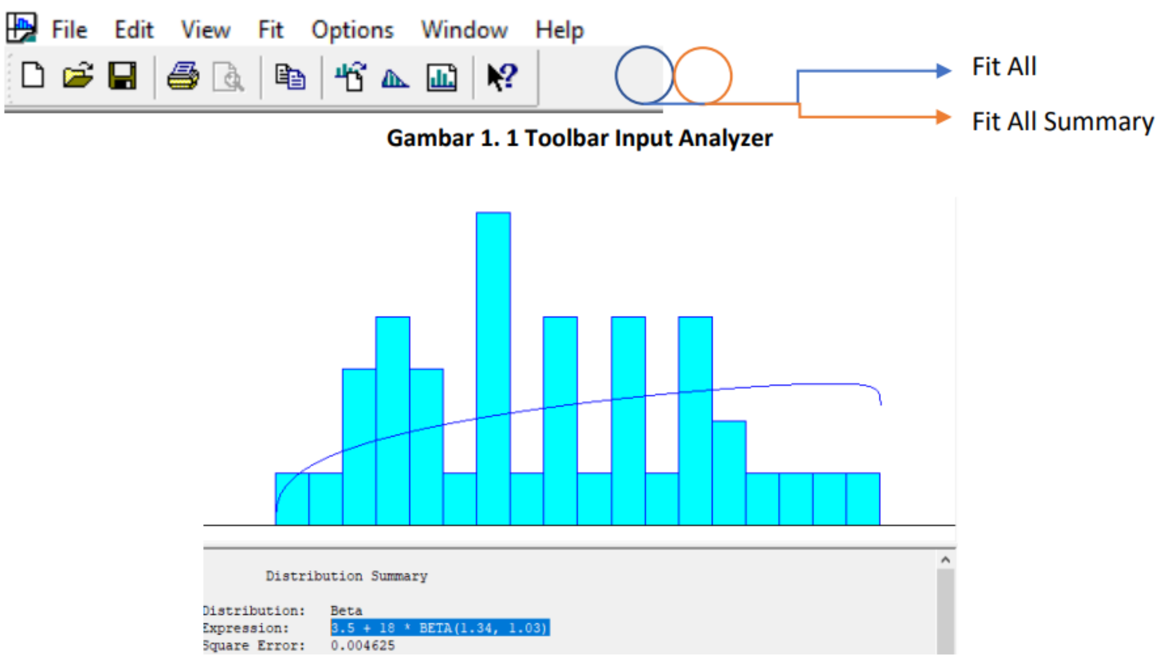
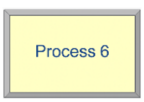
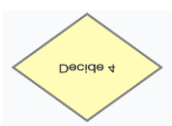


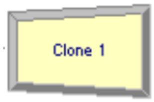
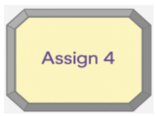
Figure 8. 1: Result from input analyser

In addition to data fitting, ARENA offers various modules that facilitate different aspects of the simulation. These modules allow for the definition of entities and their attributes, resource allocation and management, specification of variables, and control of the system's activities. By utilising these modules effectively, the simulation model can accurately represent the ship recycling process and provide valuable insights for optimisation. Some key modules used in ARENA for ship recycling simulations are:

Table 8. 1: Key modules used in ARENA

No	**Module**	**Explanation**	**Example of application in Ship Recycling**

1	Create 	This module initiates the arrival of entities in the simulation model. Entities can be generated based on predefined schedules or arrival times with specific distributions.	Initiate the arrival of entities (ships) in the ship recycling model
2	Dispose 	Serving as an endpoint for entities, this module represents the component of the simulation model where entities are removed or disposed of.	Represent the endpoint for entities in the recycling process, for example, metal, hazmat, waste, etc.
3	Process 	This module is used to process entities and their associated resources. It involves a sub-module that handles the entities and utilises various types of resources for processing.	Several processes such as the cutting process with x number of cutters, and x number of cutting tools.
4	Decide 	During the simulation process, the Decide module is utilised for decision-making. It allows for decisions to be made based on one or more conditions, using different approaches.	After being cut, the material needs to decide where they are going to go.
5	Batch 	Responsible for merging entities in the simulation model. It allows for the creation of both permanent and temporary batches, and the separation of temporary batches using distinct modules.	Can assist in grouping similar metals together in batches, enabling efficient processing and categorization.

6	Separate 	This module is used to separate the results of the Batch module or duplicate an entity, treating it as a separate entity stream.	Demonstrate the separation of blocks during the primary cutting process.
7	Assign 	To assign new values to variables, entity characteristics, entity types, entity pictures, and other variables within the system.	Assign different types of materials: metal, hazmat, waste, etc.
8	Record 	To display statistical data from the simulation model, including data types such as time between arrivals and other relevant metrics.	Display statistical data and metrics of the recycling process
9	Attribute Table	To define characteristics of entities, such as specific values that differentiate one entity from another. These attributes can be utilised in other modules like the Decide and Assign modules.	The Attribute table can be used to define specific characteristics of entities in ship recycling, such as the type of material or component they represent. These attributes can then be utilised in other modules like the Decide module to make decisions based on the entity attributes, such as routing or processing.
10	Entity Table	To identify and categorize different types of entities used in the simulations. They also allow for the selection of image representations to differentiate between entity types.	The Entity table is used to categorize different types of entities in ship recycling, such as different types of ships or components. By defining and categorizing entities, it becomes

			easier to track and manage them throughout the simulation model.
11	Queue Table	This table module enables the specification of queue types within a process, such as first-in, first-out, lowest attribute value, or highest attribute value. It determines the order in which items are processed in the queue	The Queue table can be employed to specify the types of queues within the recycling process such as cutting.
12	Resources Table	The Resources table is used to specify resources within the simulation system. It includes information on resource availability and cost details.	The Resources table in ship recycling allows for the specification of different resources involved in the recycling process, such as labour, machinery, or specialised equipment. It enables the simulation model to allocate and manage resources efficiently, considering factors like availability and costs.
13	Variable Table	Variables are elements within the system that can be used for calculations or sequencing entities. The Variable table allows for the management and manipulation of these variables, which can change based on the system dynamics.	Variables in ship recycling can represent dynamic elements, such as processing times, recycling rates, or environmental factors. The Variable table allows for the management and manipulation of these variables, enabling the simulation model to capture the changing nature of the recycling

			process and its impact on system performance.
14	Schedule Table	The Schedule table is used for scheduling elements that have changing values over time but remain certain. It can be employed to schedule entity arrivals in the Create module and operation times in the Resource table.	The Schedule table can be used in ship recycling to define and schedule the arrival of entities, such as ships or components, in the simulation model.
15	Set Table	This module is utilised to define various types of sets, such as resources, counters, tallies, entity types, and entity pictures. It helps organize and categorize different elements within the simulation model.	Set table can be utilised to define sets of resources, counters, or entity types. For example, it can define sets of specific tools or equipment used in the recycling process.

8.3.2 Establishing a Discrete Event Simulation in ARENA

In the simulation process using ARENA, it is essential to identify the relevant modules that contribute to the effectiveness of the simulation. These modules are designed to handle various aspects of the system being simulated and enable a comprehensive evaluation of its performance.

The interconnected elements in an ARENA simulation include entities, resources, attributes, variables, and controls. Entities represent the objects or components within the system, while resources are the assets or factors required for the system's operation. Attributes define the characteristics or properties of the entities, and variables capture the changing aspects of the simulation. Controls govern the flow and behaviour of the entities and resources within the system.

To ensure accurate and reliable simulation results, data fitting plays a critical role. The Input Analyser tool in ARENA assists in this process by providing statistical analysis and fitting techniques (Figure 8.1). It helps match the collected data with appropriate probability distributions, enhancing the accuracy of the simulation model.

8.3.3 Conceptual Model Development

Before proceeding with simulation development, it's vital to conduct field observations and gather relevant data. This process typically involves visiting the location where the process under study takes place, observing the operations, and documenting the different stages of the process. For instance, in a ship recycling study, data collection would involve detailed information about each stage such as ship arrival and administration, recycling preparation, cleaning and primary cutting, secondary cutting, segregation, and material handling.

Moreover, one should document the layout of the recycling yard, dividing it into zones according to different stages of the recycling process. Each zone is dedicated to a specific part of the process, such as primary cutting, secondary cutting, or segregation and material reprocessing. This systematic categorization helps in structuring the simulation model.

For the development of the conceptual model, five key steps of the recycling process could be identified and recorded:

1. Ship Arrival and Administration: Document the necessary administrative steps that need to be completed before the recycling process can begin, such as acquiring a sale and purchase certificate, a Gross Tonnage certificate, and a certificate of deletion of the ship.
2. Preparation for Recycling: Detail the process through which the ship is prepared for recycling. For instance, how the ship is docked, how the workers access the ship, and what safety measures are put in place before the cutting process starts.
3. Primary Cutting: Document the initial cutting of the ship, often starting from the forepeak and then continuing to the side hull. Mention the safety measures or lack thereof, such as the absence of a de-coating process which could cause fire risks during operation.
4. Secondary Cutting: This stage involves cutting the larger blocks of the ship into smaller pieces. Note the size of the pieces and the process involved.
5. Segregation and Material Handling: In this stage, materials are separated into pieces of steel, reusable materials, equipment, and waste. Record the method of segregation and how these materials are then handled, transported, and stored.

6. The detailed documentation of these steps will provide a comprehensive understanding of the process that will form the basis of the conceptual model for the simulation. This thorough understanding is vital in accurately representing the system and in achieving reliable simulation results.

To aid the data collection and to provide clarity on the areas that should be focused on during field observations, the following table outlines the critical components of each stage of the ship recycling process based on our case.

Table 8. 2: Ship recycling process components

Stage	Processes	Entities	Resources	Events	State Variables	Questions to Guide Your Study
Ship Arrival and Administration	Handling documentation (Sale and Purchase Certificate, Gross Tonnage Certificate, etc.)	Ships	Administrative personnel	Arrival of a ship	Ship queue administrative process status	How long does the administration process typically take? How many personnel are typically involved?
Preparation for Recycling	Docking process with beaching method	Ships, Workers	Yard, equipment (e.g., rope ladder)	Start of the recycling process	Ship queue, preparation process status	How long does the preparation process take? How many workers are involved in the process?
Cleaning and Primary Cutting	Cleaning the superstructure, oil and water tank; primary	Workers	Cleaning equipment, cutting equipment	Start of cleaning and cutting	Cleaning and cutting process status	How long do the cleaning and primary cutting processes

	cutting of the ship Ships,					take? What resources are necessary?
Secondary Cutting	Further cutting into smaller pieces	Ships, Workers	Cutting equipment	Start of the secondary cutting	Secondary cutting process status	How long does the secondary cutting process take? What resources are necessary?
Segregation	Separating materials into pieces of steel, reusable materials, equipment, and waste	Ships, Workers	Segregation equipment	Start of segregation	Segregation process status	How long does the segregation process take? What resources are necessary?
Material Handling	Lifting and moving of cut blocks and pieces of steel Ships	Workers	Crane, transport vehicles	Start of material handling	Material handling process status	How long does the material handling process take? What resources are necessary?

Upon completing an extensive field observation and data collection, a comprehensive process flow must be created. This process flow serves as a graphical depiction that captures the intricacies and sequential order of all the operations in the system under consideration, in this case, ship recycling. The construction of this flow is an essential step towards translating raw field data into a conceptual model suitable for discrete event simulation, following step by step as shown in the Figure 8.2 below.

Figure 8. 2: Development stages of conceptual model

1. Identify Stages: Start with identifying and listing down the distinct stages involved in the process, like ship arrival and administration, preparation for recycling, cleaning and primary cutting, secondary cutting, segregation, and material handling. These identified stages form nodes within the process flow.
2. Establish Transitions: Following this, establish transitions between these stages. This entails identifying the specific event or condition that propels progression from one stage to the next. If there are stages that can occur simultaneously or feature overlap, mark them accordingly. Alternative pathways that may arise under certain conditions should also be identified and incorporated into the flow.
3. Annotate Each Stage and Transition: Each stage and its corresponding transitions need to be annotated with relevant details documented during the data collection stage. This could include the resources used, the duration of the stage, events that signal the beginning and end of a stage, and more.

The final output should be an exhaustive and clear depiction of the system's process, from start to finish. For example, in a ship recycling study, consider the recycling process of a standard ship at a recycling yard, as depicted in a process flow diagram.

While a broad process flow is crucial for understanding the system, detailing specific processes is equally important to capture the intricate steps involved in each stage. For instance, in a ship recycling study, one such specific process that should be closely examined is the primary cutting process. The sequence of actions involved in primary cutting, and the resulting blocks, should be captured and analysed.

The primary cutting process might start offshore with the forepeak of the ship and then transition to the side hull. After this offshore cutting, the ship is pulled onshore where the remainder of the primary cutting process occurs. The resulting cut blocks are then transported to the secondary cutting zone for further processing.

Understanding these intricate details, including the sequence of cuts and the number and size of blocks created, is vital for accurate simulation. This detailed observation provides the necessary input parameters to build a realistic model, contributing to the accuracy of the overall system simulation. This reinforces the need to delve into the specifics of each stage of the process, rather than relying solely on a broad overview of the process flow.

8.3.4 Simulation Initialization and Execution

In constructing a discrete event simulation in ARENA for the ship recycling process, it is crucial to transition from the conceptual model to an operational one. This phase is initialized by outlining entities, processes, and attributes within the system, followed by executing the simulation to replicate the real-world processes.

8.3.4.1 Determining Entities and Process Definitions

The preliminary task in initializing the simulation revolves around setting up the entities. In the context of the ship recycling process, the primary entities are the ships designated for recycling. They are configured using the "Create" module in ARENA. This stage dictates the pattern of arrival and attributes of each entity.

Subsequently, attention is shifted towards defining the process flow. Utilising the Process and Dispose of modules in ARENA, different stages of the ship recycling process observed in the field are represented. In conjunction with defining the process, the allocation of resources and the design of routing logic are integral in transitioning entities between stages.

8.3.4.2 Allocation of Attributes and Schedules

The subsequent stage in the initialization involves defining the schedules and attributes within the simulation. The schedules control the availability of resources, alongside determining the operational times for various processes. Simultaneously, the routing logic is established, outlining the progression and conditionality of entities transitioning between various stages. Complementary to this, attributes are assigned to the entities to incorporate individual properties such as ship dimensions, and materials contained, among other relevant characteristics.

8.3.4.3 Running Simulation

Once the initialization stage is complete, and the schedules, attributes, and routing logic have been defined, the simulation can be run.

Running the simulation involves executing the model over a defined period, allowing the user to observe the progression of entities (e.g., ships in a ship recycling simulation) through the system. As the simulation runs, it uses the schedules and routing logic defined earlier to determine when and how entities move between stages, and it uses the attributes to determine how each entity interacts with the system.

During the simulation run, data is collected on various performance measures. These may include throughput, utilisation of resources, waiting times, processing times, and any other measures of interest. This data is typically recorded and can be used for analysis after the simulation run is complete.

Crucially, it's important to run the simulation for a sufficient length of time to ensure statistically significant results. To account for the inherent variability and uncertainty in the simulation model, multiple replications should be performed. Running the simulation multiple times provides several different outputs that consider the elements of randomness in the system.

8.3.5 Model Validation

Model validation is a crucial step in the simulation process, especially within the context of ship recycling. The ultimate objective is to ensure that the simulation model closely mirrors the actual ship recycling system in real-world operations. This is accomplished by juxtaposing the model's output with actual data from the ship recycling yard and assessing its ability to faithfully replicate the yard's behaviour and performance.

There are multiple methods to validate a simulation model, and they may be particularly applied to the ship recycling case as follows:

1. Face Validation: As an initial validation measure, this involves subject matter experts familiar with the operations of the ship recycling yard. They review the model and its

results based on their understanding of the system and their expectations. If the results align with their expertise and knowledge of the ship recycling system, it provides preliminary confidence in the model's validity.

2. Statistical Validation: This validation method involves comparing the model's outputs, such as ship processing times or material output quantities, with actual data collected from the ship recycling yard. Statistical tests are typically conducted to measure the degree of similarity. If the model's outputs fall within an acceptable range of the actual data, it lends credence to the model's accuracy.
3. Sensitivity Analysis: This process involves changing the model's inputs, such as ship arrival rates or resource allocation, to observe how sensitive the model's outputs are to these changes. If the model reacts in a manner consistent with the known behaviour of the ship recycling system, it bolsters the model's validity.
4. Operational Validation: In this form of validation, the model's ability to predict the effects of changes to the system is tested. For instance, if a change is made to the ship recycling model, like an increase in the workforce or introduction of new cutting machinery, and the model's prediction of system performance aligns with the actual observed performance when the same changes are made in the actual ship recycling yard, it further substantiates the model's validity.

8.3.6 Pinpointing the Bottleneck

Following the validation of the simulation model, the next logical step is to use this model to identify any system bottlenecks within the ship recycling process. Bottlenecks in a system are points of congestion where the work demand surpasses the system's capacity, leading to inefficiencies, delays, and reduced throughput.

To identify bottlenecks within the ship recycling process, start by studying the model's performance metrics. These may include the utilisation rate of resources, queue lengths, and wait times at various stages of the recycling process.

1. Utilisation Rates: The utilisation rate of a resource (such as a cutter or a crane) refers to the proportion of time the resource is in use. High utilisation rates often indicate a bottleneck, as it implies that the resource is constantly in use and may not be able to handle additional work.

2. Queue Lengths and Wait Times: Long queues or extended wait times at a specific stage in the process also suggest a potential bottleneck. If ships or blocks of material are consistently waiting to be processed at a certain point, it indicates that the stage is unable to handle the incoming work as quickly as it arrives.
3. Throughput: Another key metric is the system's throughput, or the number of ships processed in a given time frame. If the throughput is lower than the potential or desired rate, it may be due to bottlenecks within the system slowing down the overall process.

8.3.7 Optimisation Procedure

Upon identifying potential bottlenecks in the system and forming several improvement strategies, optimisation software like OptQuest provides an invaluable contribution. This software, integrated within the ARENA simulation environment, uses intricate algorithms to determine the optimum combination of system parameters for ideal performance.

OptQuest employs metaheuristic optimisation techniques such as Tabu Search, Scatter Search, and Neural Networks. This approach allows OptQuest to effectively explore the solution space of the simulation model, identifying the best parameter set that yields the top outcomes as per the defined performance measures.

Within the context of ship recycling, various performance measures can be optimised. These could encompass maximizing the number of ships processed within a certain time frame (throughput), minimising the average time a ship spends in the system (cycle time), or maximizing resource utilisation. Also, constraints can be defined that the solution needs to abide by, such as budgetary restrictions or resource capacities.

To utilise OptQuest, an initial definition of the decisions that need optimisation is necessary. In the scenario of ship recycling, these might include the number of cutters, the schedule for different stages, the layout of the shipyard, or any other controllable parameter that influences the system's performance.

Once the decision variables, objectives, and constraints are defined, OptQuest conducts multiple simulations, each time varying the decision variables within their defined ranges. The software records the outcomes of each simulation run and, over time, learns which combinations of decision variables lead to the best results.

After the optimisation process, OptQuest presents the best-found solution - the combination of decision variables that led to the best outcomes according to the set objectives. This solution can then be implemented in the real world, ensuring that it is an optimised strategy based on rigorous simulation testing.

8.4 Integrating Cost-Benefit Analysis with Discrete Event Simulation

The integration of Cost-Benefit Analysis (CBA) with Discrete Event Simulation (DES) provides a robust decision-making framework for evaluating system performances, as shown in the Figure 8.3 below. DES offers a detailed depiction of system operations, unveiling process flow and potential bottlenecks. Conversely, CBA evaluates the costs and benefits associated with each choice, thereby furnishing an economic viewpoint.

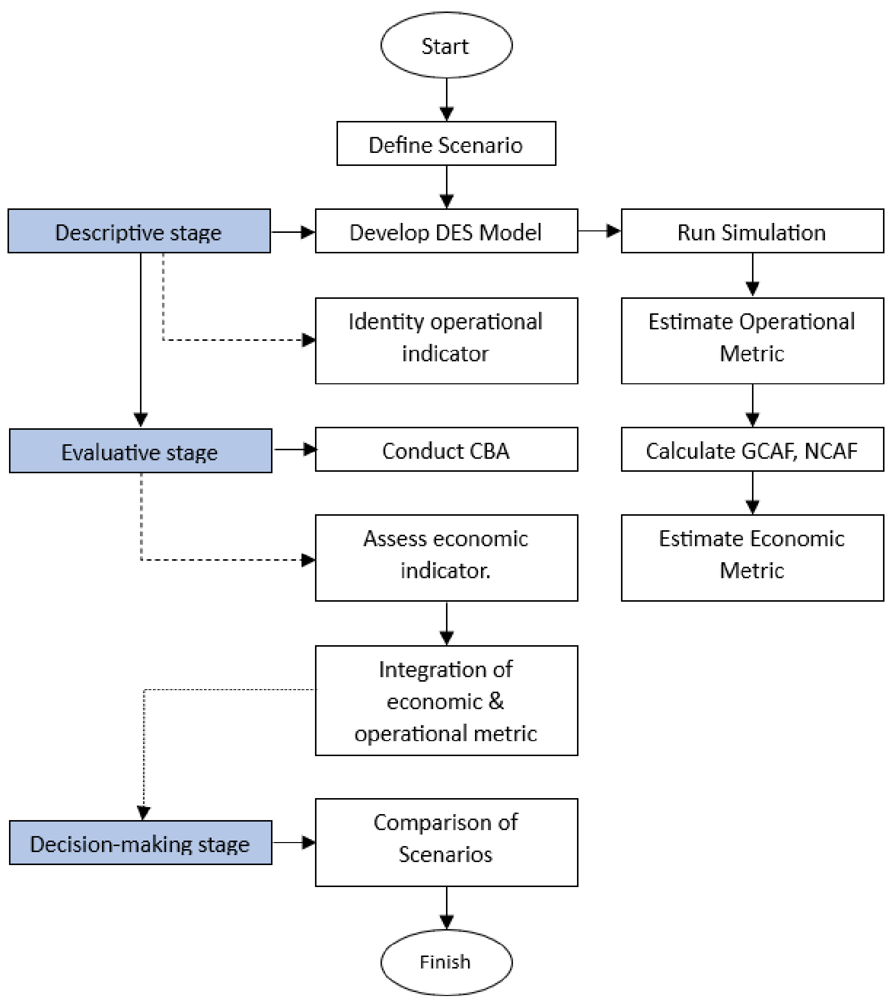


Figure 8. 3: Integrated CBA and DES in ship recycling context

To fully integrate cost-benefit analysis with discrete event simulation (DES), the process can be divided into several detailed steps. First, **scenarios are defined** by identifying different Risk Control Options (RCOs) that could be applied in the ship recycling simulation. These RCOs serve as the various scenarios to be simulated. Next, a **DES model is developed** for each scenario, outlining the schedules, attributes, and routing logic. Following this, **operational indicators** such as throughput, resource utilisation, waiting times, and processing times are identified to evaluate system performance under each scenario.

The **simulation is then run** for each RCO, allowing observation of system behaviour and collection of data on the predefined operational indicators. From this, **operational metrics** are estimated to provide quantifiable measures of system performance. Subsequently, a **cost-benefit analysis (CBA)** is conducted for each RCO as described in Chapter 7. This is followed by the **assessment of economic indicators**, such as implementation and maintenance costs, as well as potential savings, which are used to evaluate each RCO's cost-effectiveness.

Using the results from the CBA, **economic metrics are estimated**, giving a clear numerical insight into the cost-effectiveness of each RCO. The **integration of economic and operational metrics** then provides a comprehensive view of the performance and financial impact of each scenario. Finally, a **comparison of scenarios** is carried out using the integrated metrics, allowing for a detailed analysis of how the system performs under each RCO in terms of both efficiency and cost-effectiveness.

This integrated framework enables a deeper understanding of the financial implications of each risk control measure. By considering both costs and economic benefits, it supports more informed decision-making on the most effective and efficient measures to implement. Such a thorough assessment of cost-effectiveness is essential to ensure that the chosen risk controls deliver a balanced improvement in both safety and operational performance within the ship recycling industry.

8.5 Chapter Summary

This chapter highlighted the integration of Discrete Event Simulation (DES) with Cost-Benefit Analysis (CBA) in ship recycling operations. The stages of simulation, including initialization, execution, and validation were detailed, emphasizing the need for multiple runs to account for real-world variability. The process of identifying bottlenecks and seeking optimisation through optQuest was outlined. The chapter further explained the economic assessment of risk control measures using Gross and Net Costs of Averting a Fatality (GCAF and NCAF). Lastly, the chapter presented the comprehensive comparison of various scenarios to identify an optimal strategy that balances safety and efficiency.

This chapter concludes the iterative process established in this thesis by linking risk assessment and hazard identification (Chapter 5) with discrete-event simulation modelling (Chapter 6) and cost-benefit evaluation (Chapter 7). The simulation results generated here not only validate the initial risk predictions but also provide quantitative evidence to refine the prioritisation of risk control options. This creates a continuous improvement loop where risk assessment informs simulation design, and in turn, simulation outputs enhance risk management decisions. By integrating operational and economic metrics, this framework offers a unified decision-making tool that supports safer, more efficient, and economically sustainable ship recycling practices. The outcomes provide practical insights for ship recycling yard operators, policymakers, and regulators seeking to balance worker safety with operational productivity and long-term industry sustainability.

Chapter 9. Assessment of Indonesian Context and Potential for Ship Recycling Development

9.1 Chapter Overview

This chapter aims to address this gap by identifying the criteria for location selection, investigating the suitable locations for ship recycling yard development, and selecting appropriate locations for the Indonesian ship recycling industry through field studies, workshops, and targeted surveys to local and international experts. This paper investigates two-hybrid decision-making approaches and explores the potential of crisp and fuzzy TOPSIS and AHP decisional support. Seven Indonesian locations were preselected as potential candidates for ship recycling yard development, and the final decision structured under environmental, social and economic criteria. The findings are based on expert opinions and local development priorities. To incorporate uncertainty, fuzzy approaches were used too; however, significant differences were not found in the ranking of the locations among crisp and fuzzy decisional approaches.

9.2 Material and Methods

In this chapter, we use a three-stage approach to the problem of selecting an optimal site for a ship recycling yard. The first phase involves identifying decision-makers and criteria, as well as conducting a literature study. In the second step, the AHP approach was used to determine the weights of the primary and secondary criteria. In addition, the results were bolstered by a system that ensured the consistency of the accumulated decision matrices. In the third phase, we ranked the options using TOPSIS, taking into consideration the AHP-calculated criterion weights. Figure 9.1 illustrated the research methodology in this study.

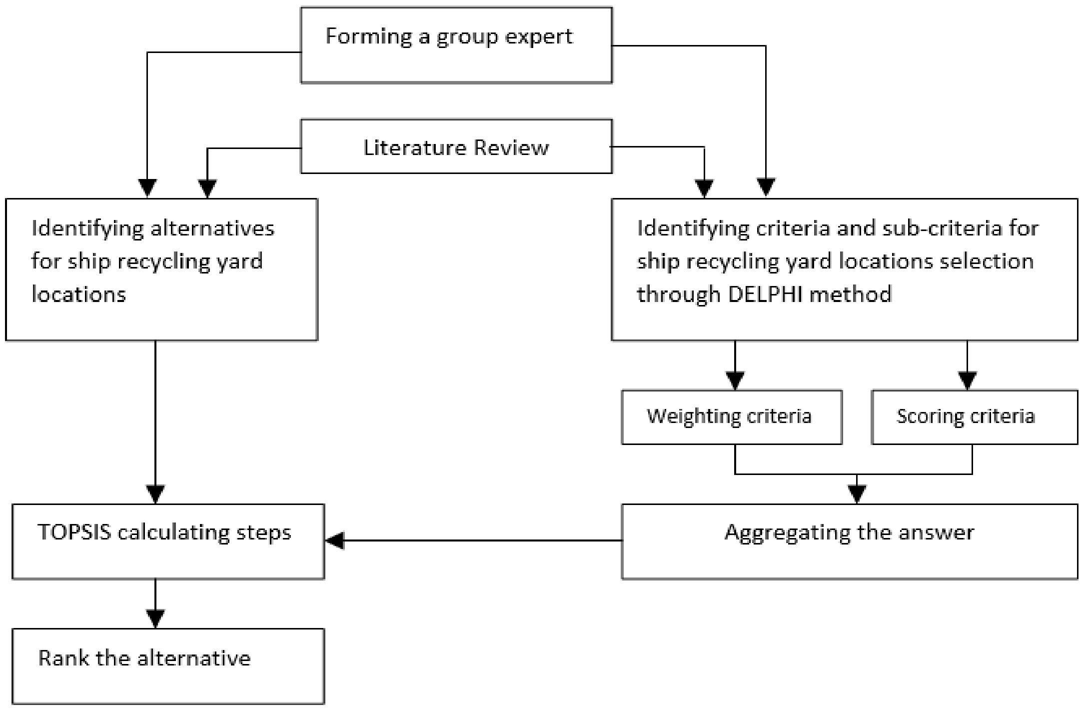


Figure 9. 1: Research methodology

9.2.1 Formation of experts group

A representative from an international non-governmental organisation (NGO) specialising in ship recycling participated in the Jakarta workshop. This individual facilitated active discussions, helped revise the workshop programme, and provided insights on additional topics to be included such as ethical considerations and economic benefits. However, further clarification is needed regarding how this expert was selected and their specific role within the workshop.

In parallel with the workshop, an electronic questionnaire was distributed to 20 carefully selected participants. These individuals were chosen based on their research and/or professional engagement with ship recycling and their comprehensive understanding of the Indonesian maritime context. Participant criteria included years of experience, occupational background, and education level.

To ensure confidentiality, all responses were anonymised, and any personally identifiable information in the free-text comments was redacted. The questionnaire was structured into two sections: the first focused on demographic information, and the second assessed each sub-criterion related to various locations. Given the integration of the questionnaire with the workshop process, the distinction between the two activities should be clarified further to avoid confusion.

9.2.2 Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy-TOPSIS)

The TOPSIS method was proposes by Chen (1981) to solve MCDM problem under uncertainty. In this paper TOPSIS was performed to assess the participants' weight of opinion. The method is based on a geographical distance from the best and worse solutions, and Euclidean distance was used. The method consists of the following basic steps:

- Standardization of the decision matrix
- Construction of a weighted standardized matrix
- Determining the ideal best and the ideal worst solution
- Determining the distance from the ideal best and ideal worst solution

TOPSIS distance from the ideal best/worst solution is the basis of the method, which develops the multi-criteria decision into a geometric system of m points and n-dimensional space. Then, the method chooses an alternative with the maximum similarity to the positive-ideal solution (Wang & Chang, 2007).

9.2.3 Identifying alternative locations and criteria

During the workshop, potential locations, including their preliminary advantages and disadvantages, were discussed. The discussions included preliminary geographical and environmental factors, such as tides, geomorphology, depth of sea level, usage of nearby ports etc., and other existing yards that could be rearranged as ship recycling yards.

The first round of questions ascertained where such a yard could be located, where every participant could provide a maximum of 2 options, and after the collection of 9 different locations, participants were asked to score these locations with a Likert scale. Furthermore, criteria and sub-criteria are chosen through the workshop.

9.2.4 Analytical Hierarchy Process (AHP)

AHP is based on pairwise comparison matrices; by scoring the relative importance of each sub-criterion to the rest of the sub-criteria, scoring each criterion to the rest of criteria, and aggregate sub-criteria, and scoring each location based on each criterion. Table 2 shows the fundamental scale of the pairwise comparison. The whole process takes a hierarchical structure by dividing sectors in alternatives, goal, and criteria, where the aggregation runs from the bottom (criteria) to the top (goal).

Table 9. 1: The fundamental of fuzzy scale (Pairwise comparison)

Triangular fuzzy importance	**Meaning**	**Explanation**
[1,1,1]	Equal importance	Two activities contribute equally to the objective
[2,3,4]	Moderate importance of one over another	Experience and judgment slightly favour one activity over another
[4,5,6]	Essential or Strong importance	Experience and judgment strongly favour one activity over another
[6,7,8]	Very strong importance	Activity is strongly favoured, and its dominance demonstrated in practice
[9,9,9]	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
[1,2,3], [3,4,5],[5,6,7], [7,8,9]	Intermediate values between the two adjacent judgments	When compromise is needed

Furthermore, AHP measures the consistency of each matrix where:

- CR is the Consistency Ratio.
- CI is the Consistency Index.
- RI is the Random consistency Index

Pairwise comparison is accepted only if this is consistent. Perfect consistency produces a zero-value of CI (CI = 0), while an accepted consistency ratio CR is less than 10% (CR < 0.1), which means the subjective judgment can be accepted. Where the CR is higher than 10%, the pairwise comparison must be performed again by changing the level of judgement.

For all the comparison matrices we calculate the CR accordingly:

(1) CR = CI/RI

(2) CI = (λmax-n)/(n-1)

λmax: maximum eigenvalue
n: order of the matrix
RI can be retrieved from Table below

Table 9. 2: Order of the matrix and random index value

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
CR	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

9.3 Case study

The case study was conducted in Indonesia, in order to demonstrate the decision-making framework to select the new location for ship recycling yard.

9.3.1 Forming a group expert.

The utilisation of expert's knowledge is used through different two approach, workshop and questionnaires. A workshop was organised in Indonesia with 13 ship recycling experts, including academics specialised in the sector, ship owners, ship recycling managers and governmental representatives, who had been invited due to their experience in the industry. For the questionnaire, 20 participants were get involved. The decision-making panel consisted of a diverse group of professionals actively involved in shipyard operations, academia, and other related sectors. The participants included experts from the academic realm, with most having an experience ranging from 0-5 years and holding qualifications varying from Bachelor's Degrees to PhDs or higher. Several participants also hailed from the shipyard, with roles such as managers, staff, and even owners, showcasing a broad spectrum of experience up to 10 years or more. Their academic qualifications were predominantly at the Bachelor's or Master's level. Furthermore, the decision process was enriched by the presence of a representative from a Non-Governmental Organisation with over a decade of experience and a Master's degree. The panel also saw participation from the ship recycling sector, encompassing roles like yard workers, managers, and owners. Their experience varied, with many holding over a decade of expertise and academic backgrounds in Bachelor's, Master's, or vocational training. To ensure a holistic perspective, a government employee with a decade of experience and a Master's degree also contributed. Lastly, a manager from a shipping company, with an experience bracket of 0-5 years and a Master's degree, was part of this eclectic group. This comprehensive mix of professionals ensured a broad-based and informed decision-making process.

9.3.2 Technique for order of preference by similarity to ideal solution (TOPSIS)

The decisional analysis starts with the weight of importance of the participants' opinions. The participants to the questionnaire were all related to the ship recycling sector; however, they present differences, and their opinions were weighted; accordingly, we scored the priority of our participants' by aggregating their years of experience, sector of profession and their level of education. Experience was considered to be more important than the specific sector of occupation and the educational level, having the following triangular numbers of priority were used: Years of experience [3,4,5], Sector of occupation [2,3,4], Level of education [1,2,3]

Table 9. 3: Ranking of participants according to fuzzy TOPSIS.

Participant	A10	A19	A6	A15	A18	A3	A5	A7	A13	A20
Score	0.818	0.800	0.788	0.788	0.741	0.680	0.484	0.484	0.484	0.451
Participant	A16	A17	A14	A12	A11	A9	A1	A2	A8	A4
Score	0.383	0.383	0.360	0.286	0.264	0.085	0.031	0.031	0.031	0.031

9.3.3 Identifying alternative locations.

Indonesia is represented by more than 17,000 islands, and thousands of them could be potential candidates. The Indonesian experts considered 7 locations which could be suitable candidates for hosting yard locations. This number (7) was achieved with the DELPHI method across two rounds of questions as mentioned in method section. The 7 Indonesian locations for potential ship recycling yards are illustrated on the map of Figure 2

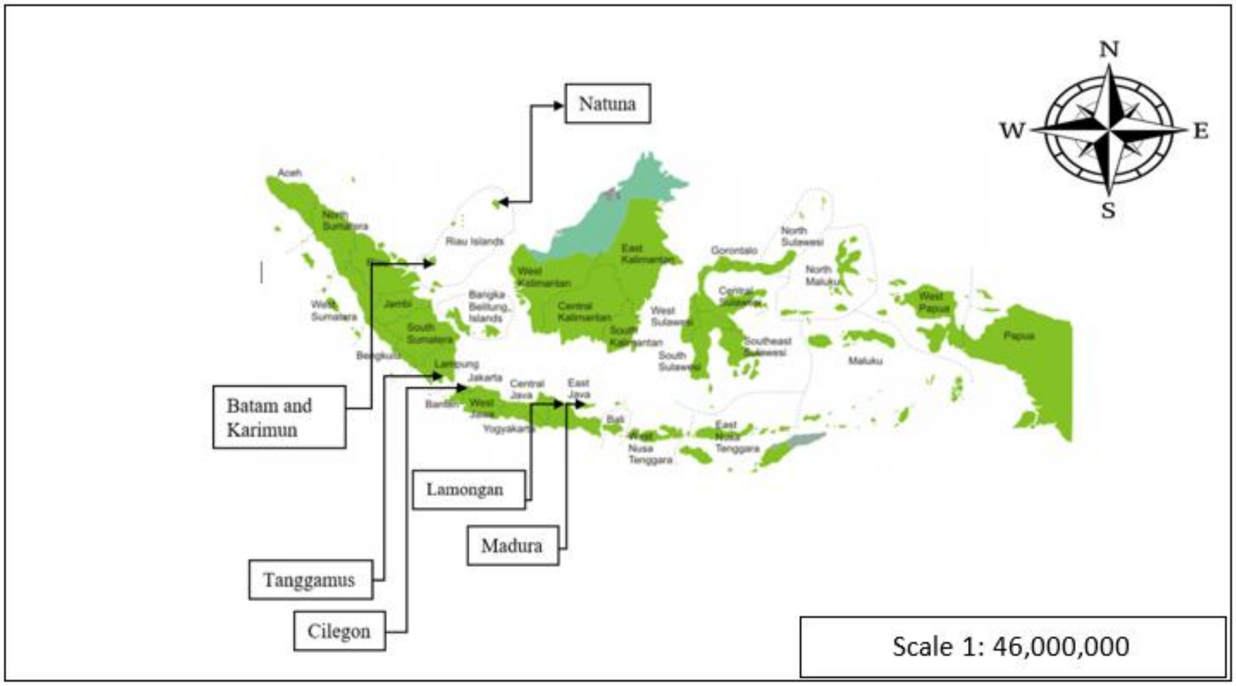


Figure 9. 2: The seven locations were preselected during the workshop in Indonesia

Furthermore, a structured and defined decision was required to select the best candidate among these 7 locations, where each was a good candidate in terms of its size, place, and population. However, considering other aspects, which are discussed later, each of the locations is accompanied by a different set of advantages and disadvantages, which were considered during the decisional analysis, and further described below.

1. Madura is an Indonesian island situated off the North-eastern coast of Java. Specifically, it can be located in Sergang, Batuputih, Sumenep Regency, East Java with coordinates (-6.868764, 113.875018). The island is notable for housing the largest ship recycling yard in Indonesia, spanning an impressive 2.5 kilometers. Given its prominence in the ship recycling industry, the local inhabitants are well-acquainted with these activities.
2. Cilegon, a prominent coastal industrial city, is situated in the Serang regency, within the Kramatwatu district. Its coordinates are (-6.01100, 106.13037). The city lies within the Banten province and is renowned for hosting the Krakatau Steel company, a linchpin in Indonesia that supplies steel for both local and global industrial needs.
3. Tanggamus, located in the Pematang sawah district of the Tanggamus regency, belongs to the Lampung Province on Sumatra Island, Indonesia. Its exact location can be determined using the coordinates (-5.65061, 104.61149).

4. The Natuna Regency, an archipelago consisting of 272 islands, can be found in the Kelarik air mali district of the Natuna regency. It sits in the southern portion of the South China Sea, more precisely in the Natuna Sea, with the coordinates marking its location as (4.017019, 107.985974).
5. Lamongan is a significant regency in East Java, identified more specifically within the Brondong district of the Lamongan Regency. Its location is surrounded by the Java Sea on its northern boundary and can be pinpointed using the coordinates (-6.871680, 112.240688).
6. Batam Island, a core urban and industrial hub within the Riau Islands Province, covers an extensive area of 3,990 km², of which 1,040km² constitutes land. The coordinates for Batam Island are (coordinate Bs 1005'N 104002'E). The island's shipbuilding industries are predominantly concentrated in Sagulung and Batuaji Municipalities. Notably, Batam is part of a free trade zone within the Indonesia–Malaysia–Singapore Growth Triangle and lies just 20 km off the southern coast of Singapore.
7. Finally, Karimun Island, a part of the Riau Islands province, falls under the administrative purview of the Karimun Regency. The island's strategic location is 37 km southwest of Singapore, 54 km west of Batam, and 64 km southwest of the Port of Tanjung Pelepas, Malaysia, with the coordinates being (1.036490, 103.326275).

9.3.4 Identifying Criteria and sub-criteria

During the workshop, a set of criteria and related sub-criteria were identified, where experts identified three basic categories of criteria: Environmental, Technical, Social and Economic, as these are aligned to the strategic targets of Indonesian development. In addition, a set of sub-criteria, which are smaller categories that specify the criteria, were also identified. The sub criteria were provided using the DELPHI method and utilised two rounds of questions. During the workshop, participants were asked to offer criteria for ship recycling yards anonymously. A set of 35 sub-criteria regarding geography, water, air and toxic material production were obtained. A second round was made to score the necessity of these sub criteria and a set of 15 was achieved, selecting those with maximum scoring (Likert scale of 5 points). The answers also satisfied the guidelines (IMO MPEC (63) 2012) for Safe and Environmentally Sound Ship Recycling, which among other suggestions, recommend: health and safety technical training to the workers, adequate and close to the yard waste treatment facilities, and healthcare providing system. These sub criteria are then divided by criteria category. The detailed of each sub criteria can be seen in Table 9.4

Table 9. 4: Criteria, sub-criteria, and their explanation.

Environmental Criteria The criteria which is related to emission and waste as well as the current condition of surrounded environment		
Sub-criterion name	No	Brief explanation
Land condition	X1	The type of ground for building preferably granular soils, including soils with sand and/or gravel content. Avoiding cohesive soil / soil comprised of silt and clay due to its tendency to shrink and swell
Sea condition	X2	For the height of the wave, ideally around 0.5 – 1 meter. Avoid areas with a huge wave. Sedimentation of soil and waterfront should be considered as well.
Waste management facilities	X5	Preferably close to the waste treatment facilities.
The availability of steel mil	X6	Preferably close to the buyer/ steel mill to reduce the transportation emission

Technical Criteria The criteria which is related to technical feasibility and supporting infrastructure		
The availability of steel mill	X6	Available high-capacity Steel mill.
Access for transportation	X10	Condition of the access road considering truck and logistic vehicle access to the yard.
Electricity infrastructure	X11	The availability of the electrical infrastructure for establishing a yard.
Freshwater supply	X12	The availability of the freshwater supply in this location.
Telecommunications	X13	The availability of the telecommunication infrastructure.

Social Criteria The criteria which is related to social welfare of workers and local people		
Vocational school	X8	Preferably close to a vocational school for training.
Hospital/healthcare facility	X9	Preferably close to the hospital/ health facilities.
Regional Minimum standard wage	X14	Regional wage standard with the minimum ones to be preferred for options of further development.
Tsunami threat	X16	Preferably located far from tsunami location/ centre

Economic criteria The criteria which is related to the cost, local economy, and market opportunities		
Incentives by Government	X15	If there is any current plan from the Government to build ship recycling or similar industries in that location.
Congest water	X17	Preferably sea water with low density
Shipping route	X4	Preferably close to shipping route and nearby port
Workforce	X7	The availability of a workforce near a location as well as their regional GDP
Depth of sea	X3	The depth of the sea is important for understanding which types of ship can reach the island (e.g. big ships cannot approach swallow water ports).

9.3.5 Analytical Hierarchy Process (AHP) Result

The next step was to structure the decision into a hierarchy according to the AHP method. Environmental, Technical, Social and Economic criteria were chosen and further subdivided into sub-criteria, which explain further the criterion itself. The priority of sub criteria was calculated by the authors. The hierarchy can be seen in figure 3, and details

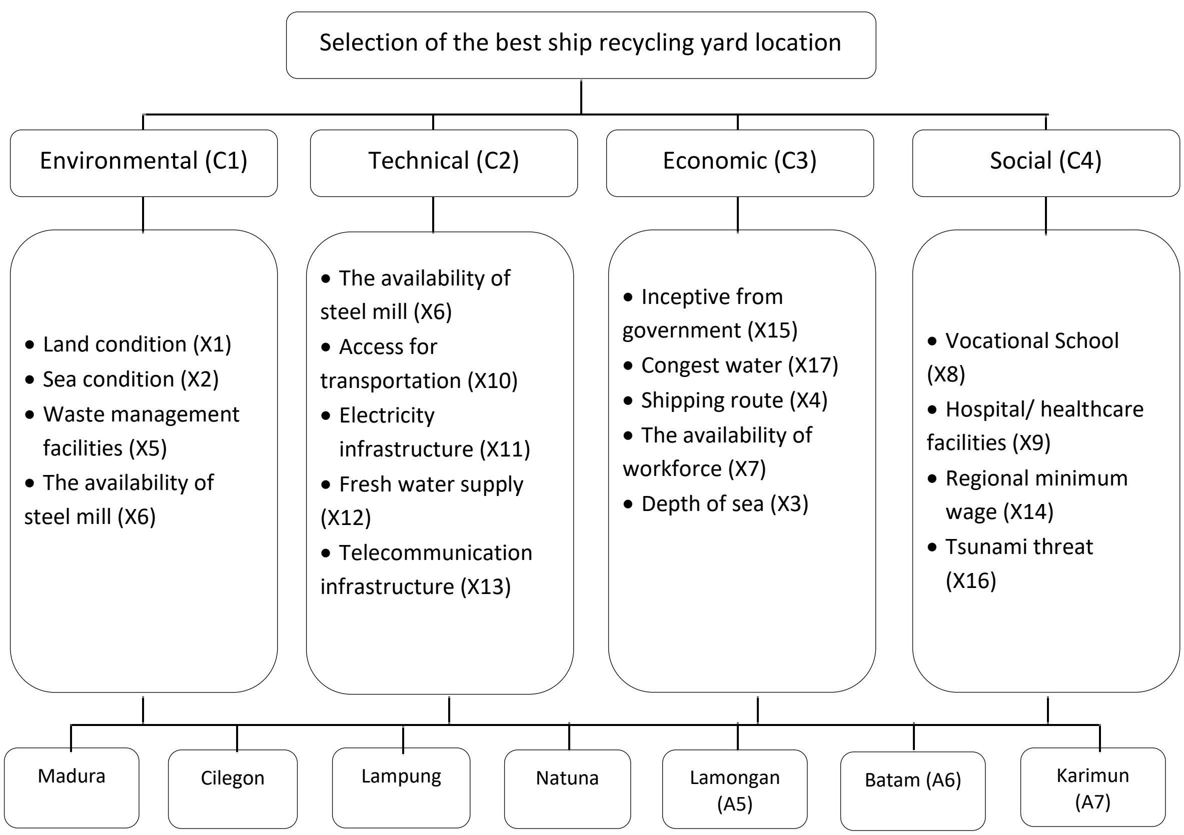


Figure 9. 3: Hierarchy of the decision making.

Furthermore, for proceeding into AHP decisional analysis, pairwise comparisons were performed (by the authors) on the sub-criteria, based on the criterion for social criteria (shown in Table 9). All criteria were subjected to pairwise comparison accordingly, and only consistent decisions were accepted; whereas no consistency had achieved, pairwise comparisons were repeated. Four matrices, one of *environmental* criteria priorities, one of *social* criteria priorities (Table 9), one of technical and one of economic were formed like the Table 9.5

Table 9. 5: Pairwise comparison for social criteria.

Social	X7	X8	X9	Rank (%)
X7	1	3	2	55
X8	1/3	1	1	21
X9	1/2	1	1	24
CR = 1.9%, λmax = 3.018				

The calculation of pairwise comparison matrices gives the results of the priority for each of the criteria, Table 9.6 give the summary of the results.

Table 9. 6: The result of priority of each criteria

Priority of environmental sub-criteria		
No	Sub-criteria	Priority
X1	Land condition	55.90%
X2	Sea condition	23.80%
X5	Waste management facilities	10.20%
X6	The availability of steel mil	10.20%
Consistency Ratio CR = 5.7% Principal eigen value = 4.154		
Priority of social sub-criteria		
No	Sub-criteria	Priority
X8	Vocational school	5.00%
X9	Hospital/ health care facilities	21.60%
X14	Regional minimum wage	17.20%
X16	Tsunami threat	56.20%

Consistency Ratio CR = 6.2% Principal eigen value = 4.170		
Priority of technical sub-criteria		
No	Sub-criteria	Priority
X6	The availability of steel mil	8.90%
X10	Access for transportation	14.40%
X11	Electricity infrastructure	19.30%
X12	Fresh water supply	50.60%
X13	Telecommunication infrastructure	6.90%
Consistency Ratio CR = 5.0% Principal eigen value = 5.224		
Priority of economic sub-criteria		
No	Sub-criteria	Priority
X15	Inceptive from government	13.60%
X17	Congest waters	30.80%
X4	Shipping route	32.70%
X7	The availability of workforce	12.80%
X3	Depth of sea	10.10%
Consistency Ratio CR = 7.2% Principal eigen value = 5.324		

Having obtained the ranking of sub criteria against each criterion, each experts' opinion against each location and the given sub criteria was aggregated. The answers regarding the opinion of each location (based on each sub-criterion) were collected from all participants, two sub criteria, tsunami threat and congestive waters were evaluated by the authors, since they were added at a later stage from the time of the questionnaire distribution. Where participants did not answer or answered as zero (0) to our questions, this was considered the lowest score one (1). This modification was important for further translating these answers into AHP decisional modelling. 20 such matrices were formed, one for each participant. Once collected the matrices, the next step was to include each participant’s weight of opinion to the score of each location against each sub criteria. Summing up the scoring of each weighted answer we formed the matrices of each location against each criterion and obtained 4 matrices as seen on Table 9.7 (one for each criterion).

Table 9. 7: Overall result for environmental sub-criteria

Environmental sub-criteria					
Location	X1	X2	X5	X6	**Results**
	Land condition	Sea condition	Close to waste facility	The availability of steel mil	
	0.55	**0.238**	**0.102**	**0.102**	
Madura	0.195	0.177	0.162	0.158	0.182
Cilegon	0.137	0.153	0.196	0.185	0.151
Lampung	0.134	0.116	0.134	0.140	0.129
Natuna	0.078	0.076	0.099	0.085	0.080
Lamongan	0.157	0.158	0.173	0.151	0.157
Batam	0.165	0.182	0.128	0.174	0.165
Karimun	0.134	0.138	0.109	0.107	0.128

Table 9. 8: Overall result for economic sub-criteria

Economic sub-criteria						
Location	X3	X4	X7	X15	X17	
	depth of the sea	ship route	workforce	Incept gov	Congest waters	
	0.136	**0.308**	**0.327**	**0.128**	**0.101**	**Results**
Madura	0.118	0.143	0.180	0.165	0.114	0.152
Cilegon	0.153	0.164	0.165	0.165	0.086	0.155
Lampung	0.143	0.143	0.137	0.165	0.257	0.155
Natuna	0.154	0.136	0.085	0.165	0.257	0.138
Lamongan	0.138	0.129	0.150	0.165	0.114	0.140
Batam	0.153	0.148	0.160	0.165	0.086	0.148
Karimun	0.141	0.137	0.123	0.165	0.086	0.131

Table 9. 9: Overall result for technical sub-criteria

Technical sub-criteria						
Location	X10	X11	X12	X13	X6	**Results**
		Electricity		Telecommunication		

	Access for transportation		Clean water		The availability of steel mil	
Madura	0.148	0.159	0.145	0.158	0.158	0.155
Cilegon	0.182	0.174	0.177	0.165	0.185	0.172
Lampung	0.123	0.128	0.130	0.145	0.140	0.137
Natuna	0.097	0.091	0.095	0.078	0.085	0.085
Lamongan	0.151	0.159	0.157	0.157	0.151	0.156
Batam	0.168	0.165	0.156	0.161	0.174	0.162
Karimun	0.131	0.123	0.141	0.136	0.107	0.133

Table 9. 10: Overall result for social sub-criteria

Social sub-criteria					
Location	X8	X9	X14	X16	Results
	vocational school	hospital	regional minimum wage	tsunami	
	0.05	**0.216**	**0.174**	**0.562**	
Madura	0.137	0.167	0.186	0.130	0.149
Cilegon	0.181	0.192	0.124	0.087	0.121
Lampung	0.124	0.120	0.157	0.043	0.084
Natuna	0.088	0.080	0.129	0.217	0.166
Lamongan	0.172	0.166	0.166	0.130	0.147
Batam	0.173	0.157	0.120	0.196	0.173
Karimun	0.124	0.119	0.118	0.196	0.162

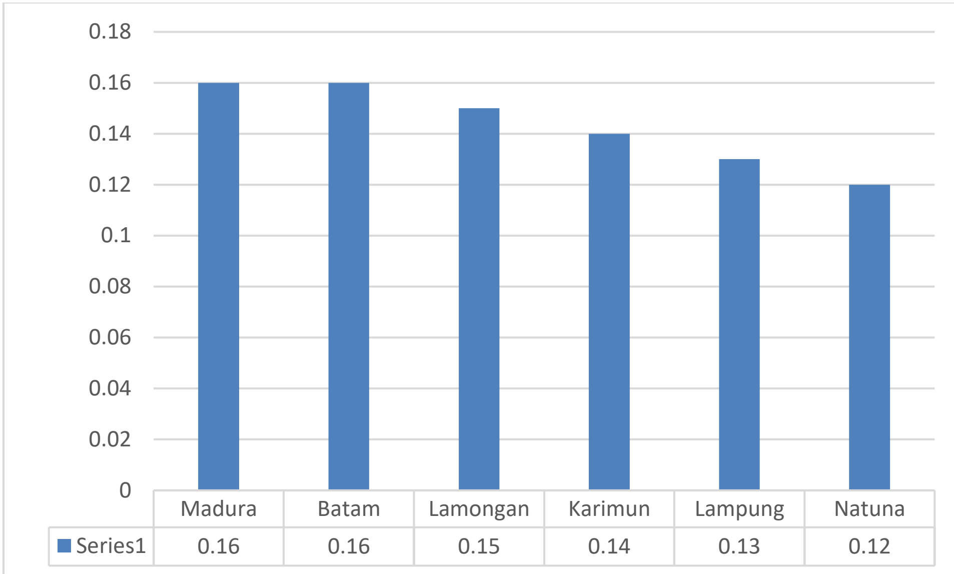


Figure 9. 4: The final rankings of locations if environmental, economic, social and technical criteria have the same weight

Table 9. 11: Equal priority to all four macro criteria

Weights				Prioritization
	Environmental	Economic	Technical	Social
Environmental	0.30	0.2	0.2	0.2
Economic	0.20	0.3	0.2	0.2
Technical	0.20	0.2	0.3	0.2
Social	0.20	0.2	0.2	0.3

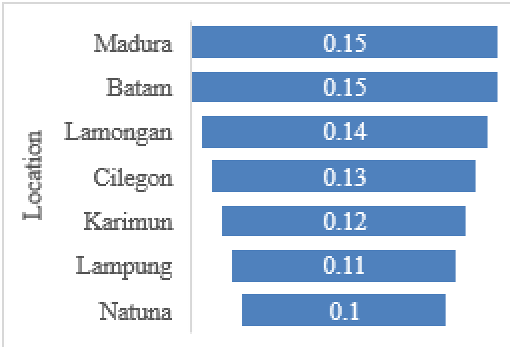


Figure 9. 8: Rank based on environmental prioritisation

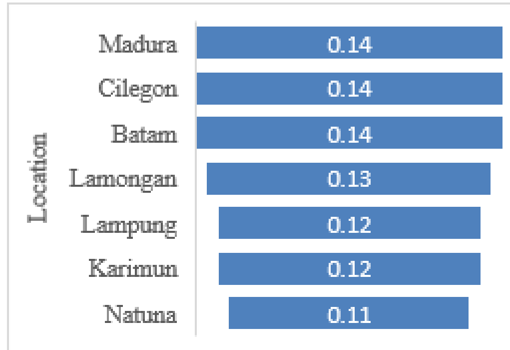


Figure 9. 7: Rank based on economic prioritisation

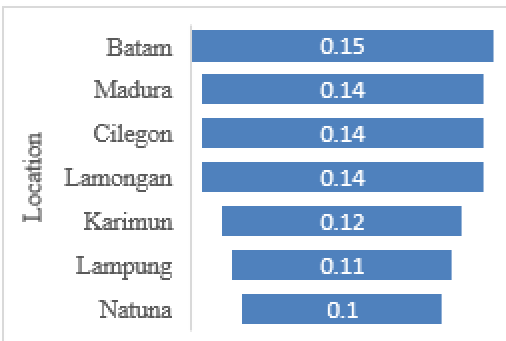


Figure 9. 6: Rank based on technical prioritisation

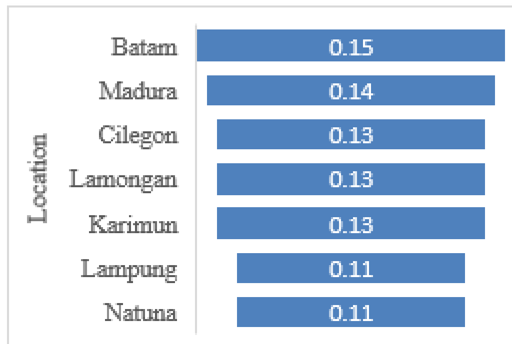


Figure 9. 5: Rank based on social prioritisation

9.4 Discussion

This chapter investigated 7 potential alternatives of Indonesian locations for building a new ship recycling yard. This kind of decisions involve many stakeholders, and they are critical for the success of the project, therefore a well-planned and structured decision is part of the strategic development of the area. The key in these decisions was the criteria and sub criteria selection and the stakeholders (or experts) valuable contribution. There are many decisional models for supporting this kind of decisions, however no model is absolutely preferable than another. There is a trend to use hybrid models for fitting the decision to the problem and optimise time and calculations needed for obtaining the best alternative. In this study, we compared the most famous and used models and we chose the AHP mainly for its hierarchy in combination to TOPSIS since for minimising the number of pairwise comparisons. The whole process was developed under the fuzzy approaches which is the preferred way to incorporate multiple stakeholders and uncertainty to the decision. Furthermore, this paper also provides a real study case in Indonesia. As a country of more than 17,000 islands, the decision-making should be performed by utilising a scientific approach for decision makers.

The analysis result shows that Madura and Batam is the highest rank if the criteria have the same weight and if the environmental is the priority. Madura is the current location of the biggest ship recycling yard industries Indonesia. Batam is also promising, as the first green ship recycling yard in Indonesia now is opening in Batam in the early of 2022 (maritime-executive, 2022). Moreover, tt is not surprise the fact that Natuna came last preference since the location faced a conflict with China. China is attempting to claim Indonesian EEZ in Natuna waters as China's traditional fishing grounds. The perception differences cause instability to Indonesian maritime security in Natuna (Darusman, et al, 2020)

For Environmental, Technical and Social prioritisation Batam is shown to be the best location for the ship recycling yard. However, if the Economic criteria are given more weight, and thus privileged, Madura seems the best option. Cilegon is ranked third if we prioritise Technical and Social criteria, and fourth and second for Environmental and Economic criteria respectively.
Batam and Madura is the 1st and 2nd rank respectively if technical as well as social criteria is the priority, as they both surrounded by established maritime industry such as the shipbuilding/ maritime yard and port. According to Ministry of industry report, Madura is surrounded by 26 shipbuilding/ repair yard nearby (kemenperin, 2022). In Batam, around 20 shipbuilding/ repair yard are established. Based on the tsunami map below (Najoan & Budiman, 2006), Batam and Madura is also safe from tsunami threat.

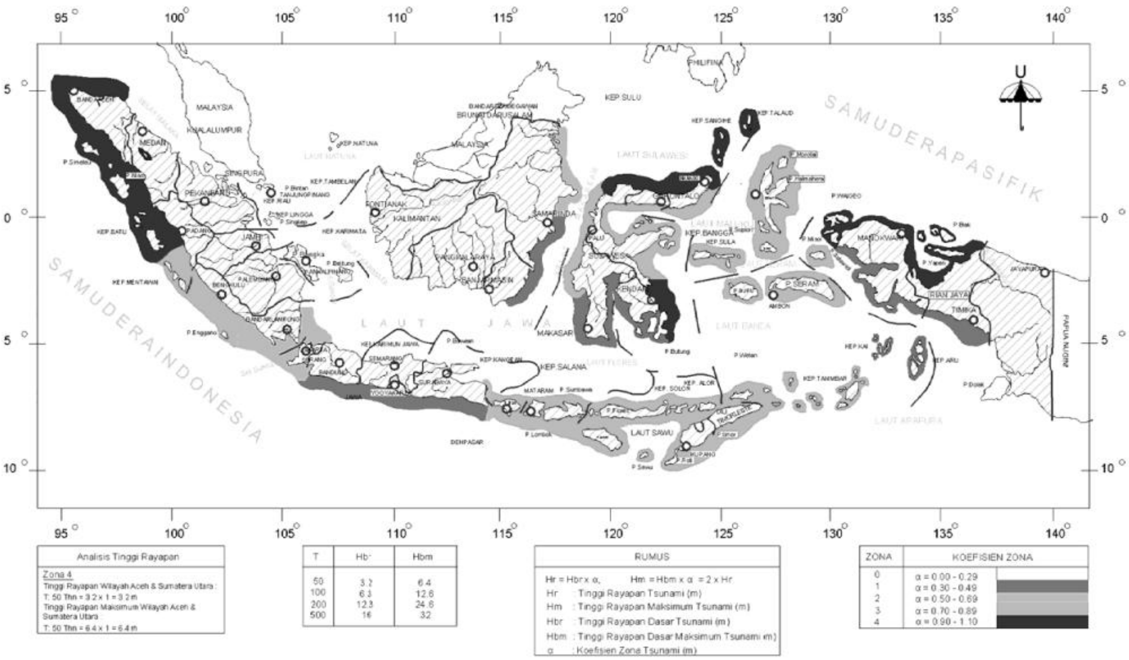


Figure 9. 9: Tsunami map in Indonesia

Madura, Batam, and Cilegon has the same rank for economic prioritization. The biggest port in Indonesia, Tanjung Priok is located near to Cilegon. Madura also lose to the second busiest port which is Tanjung Perak. As can be seen in figure below, Batam and Cilegon is located in the Sea Lanes of Communications, while Madura is close to the secondary national shipping lane.

Figure 9. 10: Indonesian shipping route map

9.5 Conclusion

Our approach provides a real case-study developed over two years of a project with frequent interactions with locals and strategic partners. We aimed to capture the necessary information for forming a clearly structured hierarchical analysis within the timeframe limits. The decision maker such as investor and government will be beneficial for this study.

The main limitation of this study is that it is based on local indexes and therefore is subjected to its case, however the hybrid frame of the decisional analysis and the procedure of capturing stakeholders´ opinion can be used for similar decisions. Another limitation is based on the core mechanism of the AHP which is only dealing with consistent decisions. Furthermore, for the future works this study can be used as a frame for location selection of similar projects, where multiple stakeholders evaluate economic, technical, social and environmental criteria for defining a strategic decision. In addition, the recent changes in the demographics and the impact of global pandemic were not taken into account due to project scope and the results are based on a case study in a developing country context, for further research suggestion similar studies can be conducted in developed country context and the impact of global pandemic can be analyse further.

9.6 Chapter Summary

This chapter supports research that encourage Indonesian ship recycling. It provides a decision-making framework for the location and operation. Sustainable engineering and site selection are two sectors where MCDM approaches have shown to be effective. In a country with over 17,000 islands, including as many decision-makers and stakeholders as possible is critical. The decision-making process began with formulating methods and reaching consensus among stakeholders who represented various groups at the time (academia, Government, economic sectors etc.). In this study, two decisional methods were built to deal with ambiguous linguistic phrases in a questionnaire.

Chapter 10. Case Study on Risk-Based Ship Recycling Yard Improvement

10.1 Chapter Overview

This chapter investigates deep into ship recycling practices at an Indonesian yard, with an enhanced focus on risk identification and evaluation. The comprehensive exploration begins by outlining the steps involved in ship recycling, detailing the resources and highlighting the associated hazards. As the intricate tasks pivotal to ship recycling are deconstructed, their interconnected hazards emerge. This lays the foundation for a subsequent in-depth risk assessment, pinpointing the most critical areas within the recycling process. Stemming from these insights, several risk control strategies are proposed, tailored to manage and mitigate these identified risks. A thorough cost-benefit analysis of these strategies and their practical application through discrete-event simulation will be addressed in the following chapter.

10.2 Describing field study.

This seminal case study offers a comprehensive insight into Indonesia's ship recycling process. Undertaken at Madura Island, the nation's biggest ship recycling centre. Spanning 2.5 kilometres along the beach, the location consists of 10 plots yards, as shown in Figure 10.1. After extensive investigations and rigorous lobbying, our team was granted rare access to the yards.

The research attempt was led by a PhD researcher, supported by two experienced colleagues. Over a dedicated month-long period, the team conducted an in-depth documentation of the recycling processes, capturing intricate details and processes. The study not only brings to light previously unavailable data but also fills notable gaps in the existing literature and industry practices. The implications of this research are significant. It not only offers valuable insights for academia but also paves the way for policy enhancements, industry recommendations, and the establishment of best practices in the realm of ship recycling. Thus, rise above mere academic value, positioning itself as an indispensable reference for future research and industry application in sustainable ship recycling within Indonesia and potentially beyond.

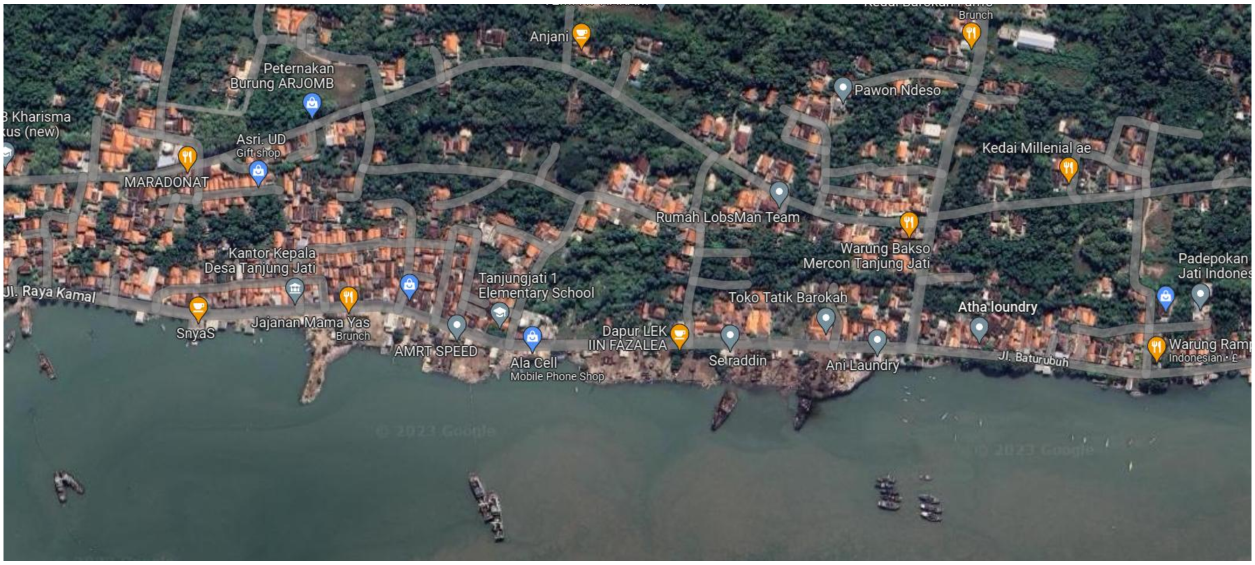


Figure 10. 1: Ship recycling yards in Madura Island

The field study involved the whole process of ship recycling process in Indonesia, which has the potential to develop into a major industry on a national and global scale (Fariya et al., 2016). The general information about the ship can be seen below.

- Ship's name : NUANSA ABADI
- IMO number : 7830583
- Ship's type : GENERAL CARGO
- Gross Tonnage : 451 ton
- DWT : 500 ton
- Classification : BIRO KLASIFIKASI INDONESIA
- Flag country : Indonesia
- Year of built : 1977
- Builder : Kamishima Shipbuilding – Japan
- L_{OA} : 48 m
- B : 7 m
- D : 4.5 m
- T : 3.2 m

Figure 10. 2: Picture of the ship for case study

10.3 Data Collection Approaches

The data collection was underpinned by three core pillars: direct observation, manufacturer consultation, and expert judgment, ensuring the validity of our findings. Prior research, including previous study was instrumental for the application of ARENA simulation in our ship recycling process analysis (Gunbeyaz, 2019). This served as a foundational reference for our work. Additionally, insights from the DIVEST and SSRI projects enriched our understanding of the methodology.

Beyond the primary study, we sought to deepen our perspective. We conducted supplementary visits to a contemporary Indonesian yard, recognized as a potential candidate for ship recycling services. This was complemented by a visit to the Indonesian Shipbuilding and Offshore Association on 23 May 2019, aiming to pinpoint challenges within ship recycling facilities. Crucially, we obtained specifications and data directly from manufacturers for equipment integral to ship recycling, such as cutting torch machines, mobile shears, winches, and cranes. Our research was further bolstered by an exhaustive review of academic literature, identifying other pertinent data sources.

10.3.1 Observation of Ship Recycling Process

This section stands as a cornerstone of our study, dedicating itself to an extensive exploration of the ship recycling process within Indonesia. With a commitment to providing unparalleled clarity, Figure 10.3 captures more than just an arrangement; it summarizes the nuanced complexities of a standard workflow widely recognized in Indonesian ship recycling yards. The depth and extent of the examination are secured in thorough observations carried out across multiple yards, setting a practice for following investigations and providing an authoritative reference.

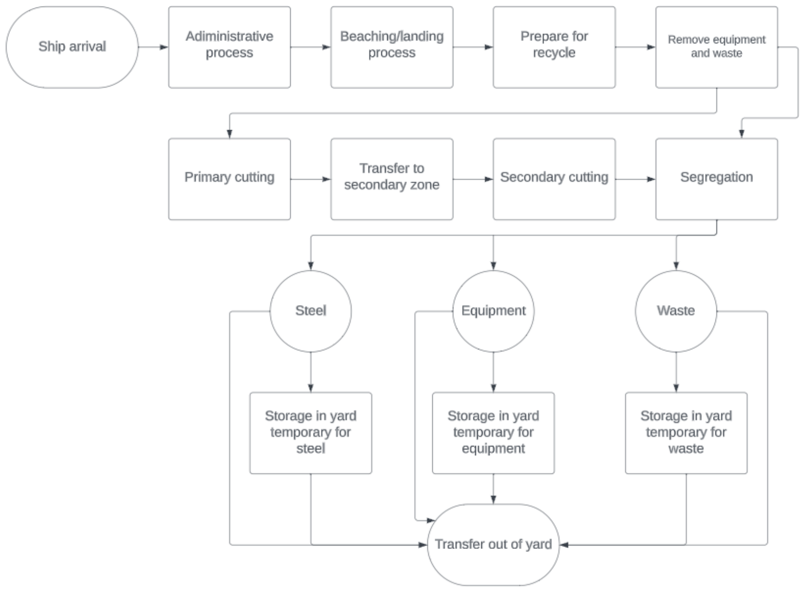


Figure 10. 3: Generic process flow for Indonesian ship recycling yard

Furthermore, based on careful observation, the ship recycling process is divided into seven distinct stages, each integral to the overall workflow as following below.

10.3.1.1 Ship arrival and administration

The arrival of a ship at the recycling yard marks the commencement of the dismantling process. This stage involves the physical docking and initial coordination required to safely secure the vessel and prepare it for subsequent procedures. It is at this point that the ship transitions from an active maritime asset to a subject of recycling operations. Although seemingly straightforward, this stage requires close coordination between the yard operators and relevant authorities to ensure that the arrival is documented, monitored, and conducted in accordance with local safety and environmental protocols.

10.3.1.2 Administrative process

Immediately following the ship's arrival, a set of administrative procedures must be completed before any dismantling can begin. These steps are crucial in ensuring that the entire recycling process proceeds in compliance with applicable legal and regulatory frameworks.

At the core of this administrative phase is the preparation and verification of documentation. These documents serve both as proof of the ship's eligibility for recycling and as a formal record ensuring the legitimacy of the yard's operations.

The principal documents required include:

- **Sale and Purchase Certificate** – This document confirms the legal transfer of ownership and authorises the ship's handover to the recycling facility.
- **Gross Tonnage Certificate** – It provides technical data on the vessel's size and capacity, which is essential for planning the recycling process and estimating the quantity of recoverable materials.
- **Certificate of Ship Deletion** – This confirms that the vessel has been officially removed from the shipping registry, a necessary condition for it to be dismantled legally.

These documents collectively provide a clear legal basis for proceeding with the recycling work. Their timely completion reflects the facility's adherence to due process and its commitment to safe, transparent, and responsible recycling practices.

10.3.1.3 Beaching/ landing process

Once all required documentation has been verified and administrative clearance granted, the ship proceeds to the beaching or landing phase. This stage involves manoeuvring the vessel from anchorage or mooring into the designated dismantling zone within the recycling yard. The method employed, whether beaching or controlled landing, largely depends on the geographical characteristics of the yard, tidal conditions, and the yard's operational capabilities.

In many South Asian recycling yards, particularly those located in intertidal zones, the beaching method is commonly used. Under this approach, the ship is deliberately driven onto the tidal mudflats at high tide and secured in place as the tide recedes. This allows the ship to rest firmly on the beach, where dismantling can begin once the vessel is stable and accessible. In contrast, facilities with dry dock or slipway infrastructure may use a landing process, whereby the ship is carefully guided into a dismantling berth using mechanical assistance.

This stage must be executed with precision, as it involves significant navigational and safety considerations. Misalignment during beaching or landing can pose risks to personnel, damage the vessel, or disrupt planned dismantling sequences. For this reason, experienced pilots and tug operators often work in coordination with yard personnel to ensure that the ship is positioned accurately. The successful completion of the beaching or landing process marks the vessel's final transition from maritime operations to material recovery. It establishes the physical context for dismantling and is often considered a symbolic moment in the ship recycling timeline.

10.3.1.4 Prepare for recycle

The preparation phase is a critical moment in the ship recycling process, setting the tone for following stages and ensuring that the recycling operations are conducted safely and efficiently. Upon the ship's arrival at the yard, the first order of business is to prepare for the docking process. The preferred method utilised is known as the 'beaching method'. In this technique, the ship is carefully navigated and positioned right where the sea meets the land. This strategic placement allows for optimal accessibility to various parts of the ship while ensuring a relatively stable working environment. It's notable that, typically, this method does not employ an impermeable floor, and there often aren't any barriers to prevent oil spills into the sea. The environmental implications of this approach highlight the importance of proper initial preparation to minimise potential ecological impacts.

Figure 10. 4: A worker is accessing the ship

As shown in Figure 10.4, workers play an instrumental role during this phase. With the ship secured in its beaching position, workers then access the ship. This access is usually granted by rope ladders, which they climb to reach different parts of the vessel. Once aboard, preliminary assessments are conducted to determine the best starting points and techniques for the upcoming cutting process.

10.3.1.5 Remove equipment and waste

Following the preparation phase, a significant step in ship recycling is the removal of equipment and the management of waste. This stage is pivotal not only to ease the subsequent cutting and dismantling processes but also to address the environmental and safety concerns related to waste, especially hazardous materials.

Figure 10. 5: Pictures of cleaning process

As depicted in Figure 10.5, which showcases various snapshots of the cleaning process, it's evident that cleaning and waste management are linked with the primary cutting phase. This integrated approach, however, doesn't include the entire ship. The main areas of concentration for these cleaning efforts are typically the superstructure, oil tanks, and water tanks. These sections are prioritized due to the potential risks they pose if not adequately cleared and cleaned. However, a concerning observation from the images and the ground reality is the evident lack of stringent procedures in handling waste, particularly hazardous materials. Rather than adhering to best practices and ensuring safe disposal, the approach seems ad-hoc, hinting at potential risks to both the environment and the workers involved. Such practices underscore the pressing need for better oversight, training, and regulations in ship recycling yards.

10.3.1.6 Primary cutting

This primary cutting stage is instrumental in breaking down the ship's vast structures into manageable sections, paving the way for following recycling or disposal phases. Figures 10.6 and 10.7 offer visual insights into the cutting activities, illustrating the complete differences between the operations conducted in the primary offshore and onshore zones.

The offshore cutting starts at one of the most forward sections of the ship, known as the fore peak. Once this region is addressed, the operation extends to the side hull. This offshore approach, while challenging due to the inherent water conditions, allows for efficient dismantling of sections that might be challenging to access once the ship is fully beached.

Figure 10. 6: Pictures of cutting activities in primary zone (Offshore)

Post these offshore steps, a critical transition ensues. The ship is methodically moved to the onshore zone, facilitated by mechanical aids such as a winch. This shift ensures better stability and accessibility, enabling workers to undertake the remaining cutting tasks with more precision and safety.

Figure 10. 7: Pictures of cutting activities in primary zone (Onshore)

However, an observation demanding attention is the absence of the de-coating process prior to cutting. The absence of this step implies that cutting operations are performed on layers of paint, coatings, and potentially other flammable materials. This practice exponentially amplifies the risk of fires during cutting, thereby elevating concerns regarding worker safety and environmental impact.

A noteworthy mention here is the dynamics of the cutting team. Each cutting task is orchestrated by a lead cutter, an individual skilled in the nuances of the cutting process. This cutter is competently assisted by a helper, ensuring smooth, efficient, and safe progress throughout the operation.

10.3.1.7 Secondary cutting

After primary cutting tasks completes, the focus transitions to the secondary cutting zone. This shift signifies a progression from initial large-scale dismantling to more nuanced and refined segmentation. As displayed in Figure 10.8, the secondary cutting operations dive into further refining the ship's larger sections. These visuals expose the detailed efforts invested in processing and reducing the initially separated parts.

Figure 10. 8: Pictures of cutting activities in secondary zone

Once transported to the secondary zone, the massive blocks go through a more precise cutting process. The aim here isn't just size reduction; it's also about ensuring that these fragments align with specific measurements that cater to recycling or disposal requirements, making them optimal for subsequent processing or sale. A standard dimension targeted in this zone, for example, is approximately 100 cm x 80 cm. Achieving such consistent dimensions not only facilitates easier handling and transport but also paves the way for standardized recycling operations, ensuring efficiency and value maximization.

It's fundamental to understand that while the secondary cutting operations might seem subsidiary to the primary actions, they are just as critical. The exactness and precision required at this stage underscore its importance in the larger ship recycling concept.

10.3.1.8 Segregation

The segregation process is a complex and vital phase in ship recycling, highlighting the overarching objective of maximizing utility and ensuring environmentally responsible disposal. Figure 10.9 provides a detailed look into this material differentiation exercise. After the ship's structures undergo reduction into more navigable sections during prior cutting stages, the real challenge of observing and categorizing these sections arises. This is not a simple exercise in section but a fundamental action that ensures each part is directed to its destination.

Core categories emerging during this phase include:

- Steel Components: These are sizable pieces predominantly comprised of steel, poised for further processing or direct recycling.
- Equipment and Reusable Materials: Often machinery or specialised fixtures, these items, depending on their condition, might be refurbished, sold, or responsibly disposed of.
- Waste: These are the residuals, often having little to no value, requiring proper disposal. However, this category demands keen attention as it houses diverse waste types, ranging from harmless to hazardous.

A point of notable concern, as gathered from observational data, is the tolerance in differentiating between waste types during segregation. The existence of general waste and hazardous materials, without clear boundaries or marking, poses significant environmental and health risks. Such practices highlight gaps in standard procedures and underscore the importance of instilling more stringent, environmentally conscious practices.

Figure 10. 9: Pictures of segregation process and reuse materials

10.3.1.9 Material handling and transfer operations

In the vast expanse of ship recycling operations, the method and mechanics behind the handling and transfer of materials play a pivotal role in determining efficiency and safety. As illustrated in Figure 10.10, one of the most commonly utilised equipment for this purpose is the crawler crane, possessing a commendable capacity of 20 tons. This machinery, designed to handle massive weight with precision, is responsible for lifting and transferring the segmented blocks and steel pieces from the cutting zones to designated areas or further processing units.

Figure 10. 10: Pictures of moving pieces of steels into the truck

However, the procedure adopted, especially in the primary zone, declares attention due to associated safety concerns. Instead of a direct lift, the methodology involves an initial downward push on the cut block, after which the crane undertakes the lifting operation. While this might seem procedural, the implications in terms of safety are profound.

This push-before-lift approach, although perhaps efficient in certain contexts, significantly amplifies the potential for accidents. The act of pushing large, unwieldy blocks poses inherent risks; materials can deviate unpredictably, posing threats to the immediate surroundings. For the workers on site, especially those in proximity to the materials, the danger of falling objects or unforeseen shifts is palpable.

Given these risks, the material handling and transfer phase serves as a poignant reminder of the intrinsic hazards within ship recycling operations. It underscores the importance of continuously reevaluating methodologies to prioritize the safety of the workforce, all the while ensuring operational efficiency

10.3.2 Detailing cutting process

Following our detailed observation of the ship recycling operation, we took to further refine and articulate the general processes previously described. The aim was to provide a granular breakdown, mapping out each specific activity and associated sequence, thus enhancing the clarity and depth of understanding for readers.

Understanding the intricacies of the ship recycling operation necessitates a close examination of the cutting process. This procedure, while seemingly straightforward, is a blend of precision, methodology, and safety protocols, all orchestrated to dismantle the colossal structures of decommissioned ships.

Step-by-step visualisation (Figure 10.10) is offering a visual journey through the cutting process, Figure 10.12 captures the continuous stages involved in primary cutting. The detailed representation, separated with orange boxes within rectangles, pinpoints the progression of the cutting operation, starting from the collision bulkhead (1) and extending up to the after peak tank (56). Furthermore, combined within the cutting process are vital cleaning activities, highlighted in yellow boxes. These activities involve a range of tasks crucial for ensuring the safe and efficient dismantling of the ship. Especially these include the removal of fuel, ballast water removal, and machinery removal. Beside cutting and cleaning, the process also demands the precise manoeuvring of the ship. Activities such as pulling the ship to the ground are crucial for facilitating optimal cutting positions and ensuring the accessibility of various ship sections.

Process Map (Figure 10.11) is complementing the step-by-step visualisation, Figure 10.11 provides a process map of the primary cutting phase. It lays out the flow and relationship between different actions, revealing the sequence, interdependencies, and potential bottlenecks within the process. These illustrations not only offer a visual representation of the cutting operations but also elucidate the depth of expertise and precision that the entire procedure demands.

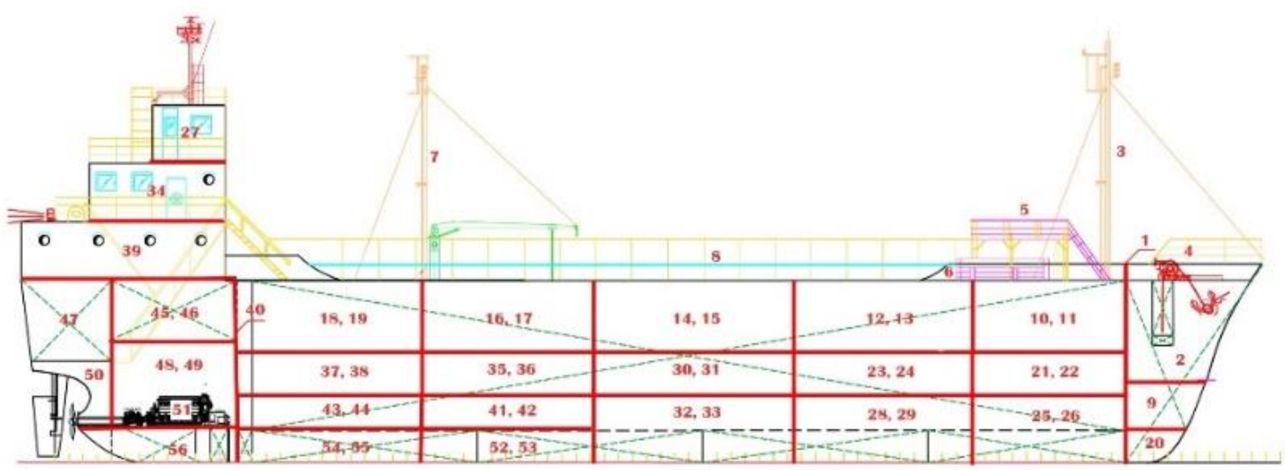


Figure 10. 11: Primary cutting process map

Figure 10. 12: Detail step-by-step primary cutting

10.3.3 Recording process time

A crucial dimension of our study revolves around accurately capturing and analysing the time taken for each phase of the ship recycling process. Beyond the descriptive visuals previously presented, Table 10.1 offers a rigorous time-motion analysis, meticulously cataloging the duration of every stage. The analysis commences with the "Preparation" phase. Unique to Indonesian shipyards, this phase intertwines the standard preparatory task with local cultural traditions and routines, setting a distinctive tone before the commencement of any work. Following this, the study delineates the duration for subsequent steps: accessing the ship, primary cutting, and the pivotal act of lifting materials. Preparation includes culture traditional/ routine before starting the job in Indonesia.

Table 10. 1: Time-motion Study Result

Process	**Time (minutes)**	**cutter**	**helper**
Preparation	1 day		
Accessing ship	10:89	2	2
Primary cutting collision bulkhead (1)	16:32	2	1
Primary cutting upper forepeak (2)	13:56	1	1
Secondary cutting forepeak on the ground	09:59	1	1
Primary cutting forecastle deck (5)	04:57	2	2
Primary cutting derrick (7)	03:12	1	1
Primary cutting Upper Hull 1 starboard (10)	20:12	1	1
Primary cutting Upper Hull 4 starboard (16)	19:58	1	1
Primary cutting bottom hull 1 starboard (21)	17:56	1	1
Primary cutting bottom hull 2 portside (22)	17:23	1	1
Primary cutting double bottom 1 starboard (25)	15:48	2	2
Primary cutting navigation deck (27)	27:45	2	2
Primary cutting double bottom 2 portside (33)	17:47	2	2
Primary cutting bridge deck	15:21	2	2
Primary cutting bottom hull 4 starboard (35)	17:32	1	1
Primary cutting machinery bulkhead (40)	14:01	2	2
Primary cutting bottom machinery space starboard (48)	19:37	1	1
Primary cutting after peak tank into 2 part (56)	30:43	2	2
Lifting forepeak block	1:29		1
Lifting Derrick	01:02		1
Lifting upper hull 1 starboard	02:03		1
Lifting upper hull 2 starboard	02:36		1

Lifting upper hull 3 portside	02:01	1
Lifting Navigation Deck	02:47	1
Lifting pieces of steel to the truck	01:36	1
Lifting pieces of steel to the truck	00:57	1
Lifting pieces of steel to the truck	01:25	1
Lifting pieces of steel to the truck	01:56	1
Lifting pieces of steel to the truck	00:54	1

It's worth noting that within this data, certain steps are infrequent and not consistently replicated across different ship recycling activities. This inconsistency introduces a degree of uncertainty in our time estimates. However, even with these uncertainties, this data serves as a pioneering resource, given the prior absence of any such detailed time-based analysis in the domain.

10.3.4 Estimating the processing time

This study systematically examines each step, providing a clear view of the time required for different stages of the process. However, it's important to note that not all data was captured comprehensively, necessitating the use of estimations. In addressing this data gap, a case-based approach for the cutting line is employed. The ship's general arrangement serves as a foundational guide. This arrangement details the ship's construction and helps in estimating cutting times. The ship mainly consists of vertical plates (like the side hull and bottom transverse) and horizontal plates (such as the bottom hull and longitudinal bottom). These plates adhere to a standard thickness. Further, the arrangement provides specifics like the length and height of the plates. Key features in this context are the side hull line, bottom hull line, and longitudinal bottom, all represented in Figure 10.12.

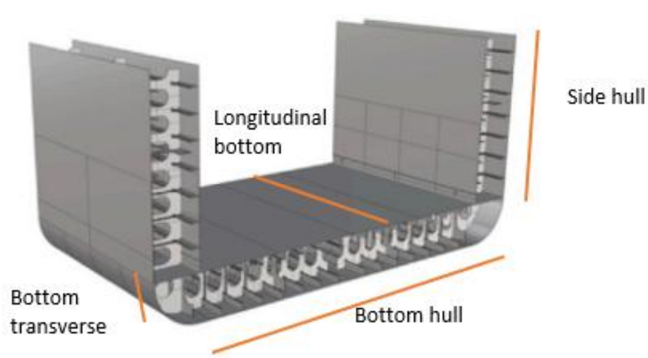


Figure 10. 13: Illustration of Cutting Line Parts

This estimation includes penetration for each girder, pre heat and reposition time with the estimation number form the observation and previous studies. The various times for each thickness came from observation, previous studies and cutting machine spec, as shown in Table 10.2

Table 10. 2: Cutting speed for each metal thickness.

Metal Thickness (mm)	**Cutting speed (mm/ minutes)**
5	750
5 till 10	750-680
10 till 15	680-600
15 till 30	600-500
30 till 40	500-450
40 till 50	450-400

Cutting lines and the distances were summarized below. For the secondary cutting, yard's current application on the maximum plate dimension was followed (1.5 meter x 0.5 meter). Yard follows these dimensions according to the steel scrap factories and their requirements.

In the context of the ship recycling process, a significant operational activity is the cutting of the ship into smaller, manageable pieces. The time taken to execute this task, known as the cutting line time, is a critical aspect of project planning and resource management. This time can be estimated using a set of parameters related to the ship and the cutting process itself, by considering the parameters as follows:

Total Line Cutting Length - This is the total length of the cutting line required, calculated for different sections of the ship, such as the Bottom Transverse, Longitudinal Bottom, bottom hull line, side hull line (starboard), and side hull line (port). Each section will have a unique total line cutting length.

- Thickness - This is the thickness of the ship's hull at the section being cut.
- Penetration Time - The time it takes for the cutting tool to penetrate the ship's hull.
- Preheat Time - This is the time taken to preheat the cutting area to facilitate easier cutting.

- Reposition Time - This is the time it takes to reposition the cutting tool from one cutting line to the next.
- Using these parameters, the total time to cut a line can be estimated using the following formula:

  Total Time = (Total Line Cutting Length * Thickness * Penetration Time) + (Total Line Cutting Length * Preheat Time) + (Total Line Cutting Length * Reposition Time)

Thus, Figure 10.14 provides a detailed overview of the total primary cutting time. This represents the initial phase where large sections of the ship are segmented, it presents a box plot of total primary cutting times across the 36 ship blocks, overlaid with individual data points to illustrate variation between blocks. The distribution reveals that the majority of blocks fall within a relatively narrow interquartile range of approximately 16 to 20 minutes, with a median around 17.5 minutes. However, several outliers are present at both ends of the spectrum. For instance, Block 1 (2.7 minutes) and Block 18 (5.6 minutes) recorded significantly lower cutting times, while Block 16 and Block 20 exceeded 25 minutes. These variations may be attributed to differences in structural complexity, steel thickness, block size, or accessibility. Simpler blocks with minimal internal fittings and flat surfaces are likely to require less time, whereas more complex or reinforced blocks, particularly those containing compartments or additional support elements, demand more time and effort. This analysis underscores the importance of block-specific planning in ship recycling operations to ensure efficiency and effective resource allocation

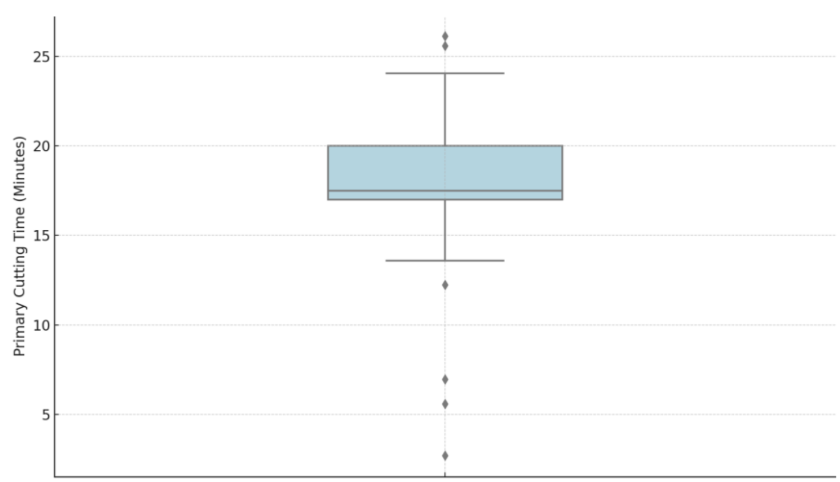


Figure 10. 14: Total primary cutting time

As one moves to Figure 10.15, the focus shifts to the total secondary cutting time. The majority of blocks required between 20 and 250 minutes to complete secondary cutting, with consistent patterns observed across similar structural components. However, several blocks stand out as significant outliers. Most notably, Block 35 recorded the highest cutting time at approximately 2,042 minutes, followed by Blocks 29 and 34, both exceeding 800 minutes. These extreme values are likely indicative of more complex structures, such as denser reinforcements, intricate internal compartments, or double-bottom configurations requiring additional time and precision to dismantle. In contrast, blocks with shorter cutting times may have consisted of simpler flat sections or previously weakened areas due to earlier cuts. This wide range of durations underscores the need for careful planning and allocation of resources, particularly for blocks identified as high-effort components during initial assessments.

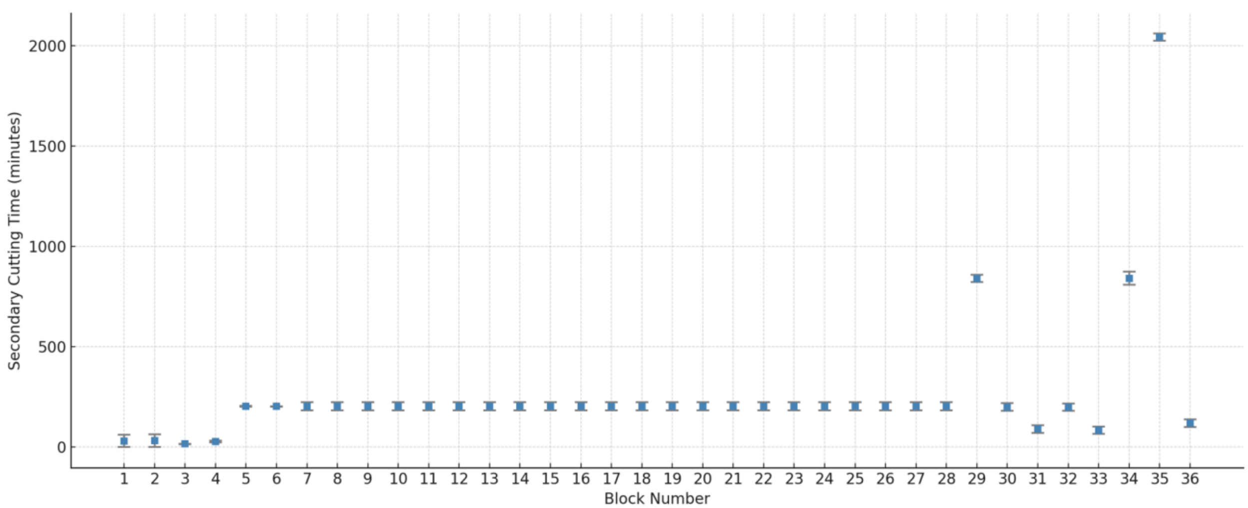


Figure 10. 15: Total secondary cutting time

10.4 Expert's gathering and weighting.

Having gathered comprehensive process data in the preceding sections, which serves as the foundation upon which we will build our simulation process for the case study titled, "Employing Discrete Event Simulation in a Cost-Benefit Analysis Framework", the focus now transitions to the key component of risk assessment. As mentioned in Chapter 7, the overarching framework commences with Hazard Identification, followed by a structured approach to Risk Analysis and Risk Control Options.

To ensure the effectiveness and thoroughness of our risk assessment, we convened a specialised team of experts well-versed in ship recycling nuances. This assembly was privy to a detailed suite of documentation encompassing all tasks highlighted earlier. As illustrated in Figure 10.3, the team boasts a diverse skill set: encompassing 2 ship recycling specialists, 3 dedicated researchers, and a singular expert in health, safety, and environment.

Table 10. 3: Participants to the decision

Interviewee	Profession	Years of experience	Level of education
A1	International academia (University Scholar, Staff, Management	10+ years	Ph.D. or higher
A2	International academia (University Scholar, Staff, Management)	10+ years	Ph.D. or higher
A3	Local academia (University Scholar, Staff, Management)	0-5 years	Master's Degree
A4	Local Industry (Ship recycling yard owner, manager)	10+ years	Master's Degree
A5	Local Industry (Ship recycling yard owner, manager)	0-5 years	Bachelor's Degree
A6	Local Industry (HSE expert)	0-5 years	Master's Degree

To further refine our analysis, the TOPSIS ranking method to assign weights to the contributions of each expert is employed. The rationale and justification for the use of TOPSIS in this context have been extensively addressed in Chapter 7. The specific weights assigned via this method are delineated in Figure 10.4, ensuring that our risk assessment is both balanced and rooted in expertise.

Table 10. 4: Expert's weight based on TOPSIS analysis.

E1	E2	E3	E4	E5	E6	E7
0.2	0.2	0.13	0.13	0.13	0.1	0.1

10.5 Hazard Identification

As mentioned on structured framework development part, the objective of the hazard identification phase is twofold. Firstly, it aspires to generate a comprehensive list of risks, complete with related scenarios, specifically ranked by their level of risk for the given situation. Secondly, it aims to show a tailored hazard identification system, thoroughly designed for ship recycling.

To optimise the process of hazard identification, we engaged our team of experts, directing them towards a pre-compiled list provided in Appendix 7. For further clarity and guidance, we offered the experts a thorough list of detailed job tasks pertinent to the ship recycling process, which can be referenced in Appendix 1. The overarching objective of this case study centred on the detailed subdivision of blocks/sections into smaller pieces within the secondary zone. This primary operation encompassed three distinct job tasks:

1. Cutting block/ section into smaller cut including cutting with cutting torch
2. Loading the pieces of steels into truck
3. Segregating materials

Post this exhaustive process, we successfully enumerated the hazards associated with these tasks, which have been presented in Table 10.5

Table 10. 5: Identified the hazards involved in each job task and causes for each hazard

Job Task 1: Cutting hull structure into smaller cut including cutting with cutting torch			
No	Hazard	No	Causal Risk Factor
1	Fire, explosion from ignited insulation, matting, lagging, and residual fuel; and lubricants and other flammable liquids.	1.1	Fire from the torch travelling back in the pipe and exploding gas cylinder
		1.2	Flammable materials, due to rest of fuel
		1.3	Flammable due to paint
		1.4	Lack of appropriate emergency response, rescue and first aid personal services
		1.5	Unprotected disposal/storage place of e.g., fuel, oil, grease
2	Burning	2.1	Hot surfaces
3	Falling on the same level-stumbling, slipping etc.	3.1	Slipping on wet surfaces or on something laying or fastening on the walking surface
4	Exposure to hazardous materials	4.1	Lack/improper wearing of PPE
		4.2	Exposure from hazardous material (Heavy and toxic metals (lead, mercury, cadmium, copper, zinc, etc.),
		4.3	Exposure from cutting fumes
5	Squeezing or crushing	5.1	Stuck by falling object

6	Penetration of sharp objects	6.1	Sharp-edged tools
7	Exposure that can give effects in a long term: Hazardous Physical situation	7.1	Noise from cutting torch
8	Hazardous Mechanical situations due to lack of maintenance	8.1	Hose, gas cylinder
9	Hazardous handling, overloading of part of the body	9.1	Awkward position
		9.2	Handling heavy objects
Job Task 3: Loading the pieces of steels into truck			
10	Hazardous handling, overloading of part of the body	10.1	Handling heavy objects
11	Penetration of sharp objects	11.1	Sharp objects and Sharp-edged tools
12	Impact with a flying object	12.1	Being crushed by flying object
13	Squeezing or crushing	13.1	Stuck by moving objects, caught in or compressed, Shackles, hooks, chains, Cranes, winches, hosting and hauling equipment

Job Task 2: Segregating materials			
14	Exposure to hazardous materials	14.1	Lack/improper wearing of PPE
		14.1	Exposure from hazardous material (solids)
		14.3	Exposure from hazardous material (liquid)
15	Penetration of sharp objects	15.1	Sharp-edged tools
16	Hazardous handling, overloading of part of the body	16.1	Awkward position
		16.2	Handling heavy objects

10.6 Risk Assessment

Following hazard identification step, the next phase required quantifying the frequency and occurrence of each identified hazard. To achieve this, data from expert questionnaires is sourced.

Experts scored Frequency (F) and Severity (S) using scales from Chapter 7. Scores were aggregated and used to calculate a risk index (F × S, or F × S × D where detectability was relevant). Higher values indicate higher-priority hazards for control. The collated findings from these insights are systematically presented in Table 10.6 below.

It is important to mention that the qualitative approach was adopted for determining the levels of probability and severity of the hazard impact. For a more in-depth understanding of this approach, we refer to Tables 7.1 and 7.2 in the framework development chapter. These tables provided the foundational guidelines in categorizing and analysing the assessed risks.

Table 10. 6: Score frequency and severity from experts

No.	**E1**		**E2**		**E3**		**E4**		**E5**		**E6**	
	F	S	F	S	F	S	F	S	F	S	F	S
1.1	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**	**1**	**5**
1.2	4	4	4	4	3	3	3	3	4	4	4	3
1.3	5	2	2	2	3	2	3	2	2	2	3	2
1.4	2	5	2	4	1	5	1	5	2	4	2	4
1.5	3	4	3	3	4	3	4	3	2	2	2	2
2.1	5	2	5	2	4	1	4	1	5	1	5	1
3.1	3	1	3	1	4	1	4	1	4	1	3	1
4.1	5	1	4	1	4	1	4	1	4	1	4	1
4.2	5	1	4	1	4	1	4	1	4	1	4	1
4.3	2	2	2	2	2	2	2	2	2	3	2	2
5.1	2	5	4	1	4	1	4	1	4	1	4	1
6.1	3	2	3	2	4	2	4	2	3	2	3	2
7.1	5	1	5	1	5	1	5	1	5	1	5	2
8.1	3	1	3	1	3	2	3	2	3	1	3	2
9.1	5	2	5	2	4	1	4	1	5	1	5	1
9.2	5	2	5	2	4	2	4	2	5	2	4	2
10.1	5	2	5	2	4	2	4	2	5	2	4	2
11.1	5	2	4	2	4	2	4	2	5	2	4	2
12.1	1	5	1	5	1	5	1	5	1	5	1	5

13.1	1	5	1	5	1	5	1	5	1	4	1	4
14.1	5	1	5	1	4	1	4	1	5	1	5	1
14.2	5	1	5	1	4	1	4	1	5	1	5	1
15.1	3	1	4	2	3	2	3	2	4	2	3	2
16.1	5	2	5	2	4	1	4	1	5	1	5	1
16.2	5	2	5	2	4	2	4	2	5	2	4	2

Table 10.9 presents the priority ranking for the analysed machine exclusively based on the conventional FMEA methodology. The RPN (Risk Priority Number) values, denoted as C-RPN, are derived from the established risk indexed parameters: Severity (S), Occurrence (O), and Detection (D). The conventional FMEA approach calculates the RPN values as the direct product of these risk parameters.

An evaluation of the RPN values reveals that Hazard 1.2 (Fire) is a particularly prominent concern. It registers the highest RPN, marking it as the top priority to address in the conventional methodology.

Table 10. 7: Risk priority number values.

No Hazard	**Conventional**	
	CRPN	Rank
1.1	5	16
1.2	13.46254	1
1.3	6.482759	14
1.4	8.003567	7
1.5	8.489893	6
2.1	6.825208	10
3.1	3.413793	25
4.1	4.344828	23
4.2	4.344828	24
4.3	4.482759	21

5.1	6.806183	11
6.1	6.62069	12
7.1	6.551724	13
8.1	4.448276	22
9.1	7.491082	8
9.2	9.034483	2
10.1	9.034483	3
11.1	8.62069	5
12.1	5	17
13.1	4.586207	20
14.1	4.827586	18
14.2	4.827586	19
15.1	6.183115	15
16.1	7.491082	9
16.2	9.034483	4

10.7 Risk Control Options

The workshop was orchestrated following a structured and methodical approach, harnessing the Delphi Technique. This technique is renowned for extracting informed opinions and insights from a group of experts, ensuring a well-rounded understanding of the topic at hand.

Workshop Procedure using the Delphi Technique:

1. Preliminary Round: Prior to the workshop, each expert was provided with a detailed dossier encompassing current literature, data, and preliminary findings related to fire accidents in the secondary cutting zone. This helped in setting a baseline understanding for everyone.
2. First Round of Responses: At the workshop's outset, participants were asked to list potential risk control options (RCOs) based on their expertise, without conferring with their peers.

3. Compilation and Feedback: All responses were anonymously compiled and presented. Each participant received a summary of these findings without revealing individual contributions.
4. Second Round of Discussion: Experts were then encouraged to discuss the compiled list, highlighting pros, cons, feasibility, and potential effectiveness of each suggested RCO.
5. Ranking and Prioritization: Post-discussion, each expert was tasked with ranking the RCOs based on their potential impact and feasibility.

Selection of RCOs:

The determination of the final RCOs incorporated:

1. Efficacy: Evaluating the potential of each RCO to substantially diminish fire accident risks.
2. Feasibility: Assessing the practicality of RCO implementation considering various constraints such as financial, technical, and operational aspects.
3. Expert Consensus: Weighing the degree of expert agreement concerning the value and feasibility of the RCO.
4. Safety and Compliance: Assurance that the RCOs conformed to prevailing industry standards and regulations.

These intensive discussions and evaluations culminated in the identification of the top RCOs, which are detailed in the table below:

Table 10. 8: Risk control options for fire accidents

Risk Control	Name	Description
RCO1	Mobile shear cutting	New cutting technology adaption
RCO2	Cleaning Process	Additional cleaning process before cutting.

RCO3	Providing fire extinguishers on the working site	Portable fire extinguisher, sand, water bucket

Moving forward:

- With RCO1 (Mobile Shear Cutting), a deeper dive will be conducted within the arena to analyse its potential impacts on the process model.
- RCO2 (Cleaning Process) and RCO3 (Providing Fire Extinguishers on the Working Site) will undergo risk experimentation. This experimentation will be visualised and illustrated using logic boxes to ensure clarity and ease of understanding for stakeholders.

10.8 Potential Loss of Life Calculation (Benchmark condition)

Examining into the particulars of potential hazards within the secondary zone, we've thoroughly constructed an event tree, showcased in Figure 10.16. This event tree was not just a theoretical effort but was deeply rooted in field observations, ensuring its relevance and practicality. Event tree analysis was used to combine the initiating event frequency, branch probabilities, and fatality probabilities to estimate individual risk and potential loss of life. Individual risk (IR) for each scenario was calculated as the product of the scenario frequency and the conditional fatality probability. The potential loss of life (PLL) was then calculated by summing the individual risks across all scenarios and multiplying by the number of exposed persons. PLL represents the expected annual fatalities and forms the basis for evaluating control options.

Our design intricately incorporates four critical safety systems to robustly counteract and mitigate the consequences of fire. These are:

- Type of Fire (TF): This categorizes and identifies the specific nature and category of the fire, allowing for tailored responses.
- Early/Timely Identification (IE): A crucial system that underscores the importance of detecting fire outbreaks as soon as they occur, facilitating immediate action.
- Firefighting (FF): This represents the active measures in place to combat and contain the fire.

- Evacuation and Escape (EE): A system emphasizing the safeguarding of personnel, ensuring swift and safe evacuation when faced with fire threats.

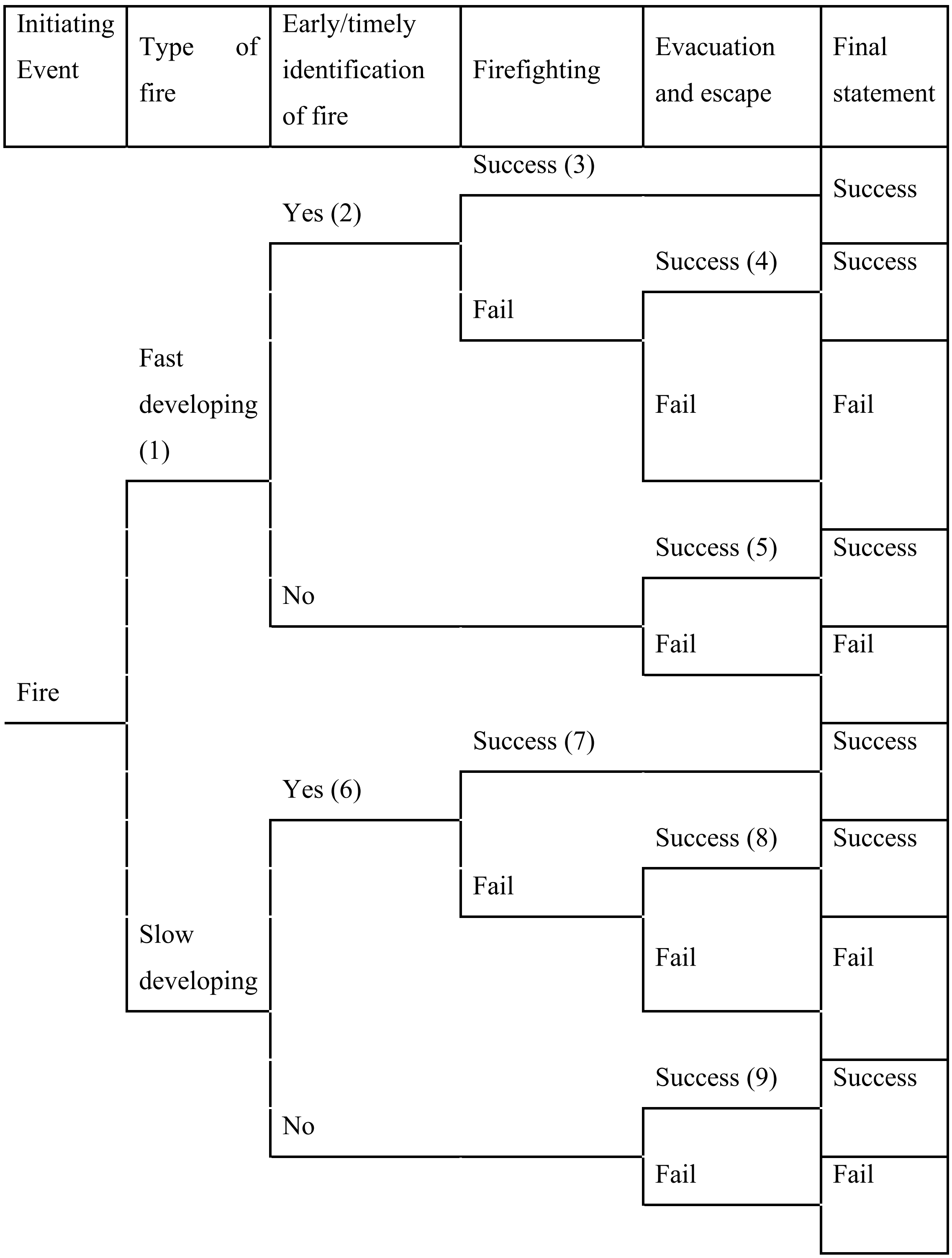


Figure 10. 16: Event tree structure

Step 1. Evaluate initiating event frequency.

The "initiating event" refers to an event that sets into motion a sequence of conditions that, if left unchecked, could lead to an undesirable outcome – in this case, a fire. To comprehensively understand and quantify the likelihood of occurrence of such an initiating fire event, a panel of seven experts was arranged. These experts were chosen based on their proficiency and experience in the realm of fire safety and risk assessment. Their task was to qualitatively assess the probability of a fire event occurring by considering six predefined failure possibilities, which are shown in Table 10.9. Formally, the expert set can be represented as:

$E = \{ei \mid i = 1,2, ..7\}$……………………….(1)

Each expert's individual evaluation and justification regarding the likelihood of the initiating event can be found detailed in Table 10.9 It's crucial to note that the scale used by these experts to determine the likelihoods is documented in Table 7. 4. This scale provides a standardized frame of reference, ensuring consistency and clarity in the evaluations provided by the expert panel.

Table 10. 9: Likelihood occurrences justified by experts

Experts	**Fire occurrence likelihoods**
e1	Quite unusual
e2	Quite unusual
e3	Quite frequent
e4	Quite frequent
e5	Quite unusual
e6	Quite frequent
e7	Quite frequent

Furthermore, using (1) and Table 10.11, the assessment of occurrence likelihood of fire can be seen in Figure 10.20 as the total frequency of fire in secondary zone is 4.95 times/ year.

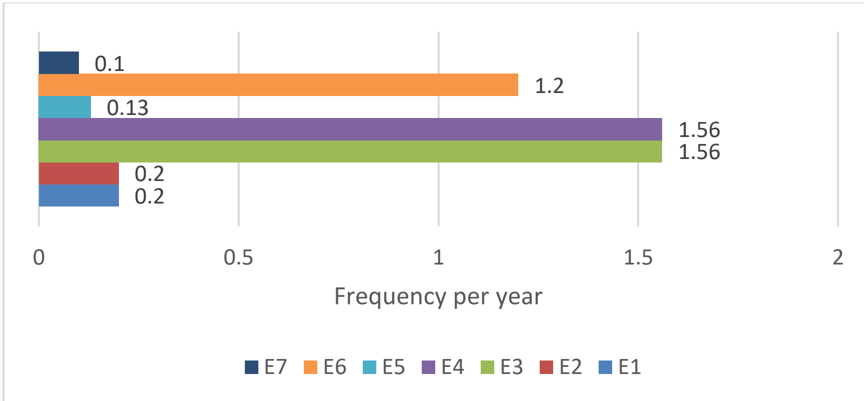


Figure 10. 17: Frequency per year defined by experts.

<u>Step 2 and 3: Quantify fuzzy probabilities of safety systems which success and fail to mitigate the initiating event.</u>

As previously noted, the fire mitigation strategy for the secondary zone encompasses four vital safety systems. Moving beyond their identification, these steps aim to quantify their effectiveness in the face of a fire event.

Each system's success probability, given the complexities and unpredictable nature of fire incidents, isn't always absolute. Instead, it's more appropriate to view them through a 'fuzzy' lens, accounting for the inherent uncertainties.

Using Figure 10.20 as a reference, experts assessed the likelihood of each safety system successfully mitigating an initiating fire event. This assessment yielded a set of probabilities, where each system is associated with a success rate. Formally, our safety system set is denoted as:

SS = {ss1, ss2, ss3, ss4} = {TF, EI, FF, EE}……………………….(2)

Those justification in 10.10 are delivered by expert's judgement for the probability of success for each node in Figure 10.20

Table 10. 10: Linguistic result for success probability for each node

Node	**Event**	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**
1	TFs	Moderate	Moderate	Moderate	Moderate	Reasonably high	Reasonably high	High

2	EIs (if TFs)	Low	Low	Reasonably Low	Reasonably Low	Low	Low	Very Low
3	FFs (if EIs, TFs)	Low	Low	Low	Low	Very Low	Low	Moderate
4	EEs (if FFf, TFs, EEs)	Reasonably Low	Low	Low	Reasonably Low	Low	Low	High
5	EEs (if EEf, TFs	Low	very low	Low	Very low	Very Low	Low	Very low
6	EIs (if TFf)	High	Reasonably high	High	High	Reasonably high	High	High
7	FF (if EIf, TFf)	High	Reasonably high	High	Reasonably high	Reasonably high	High	High
8	EEs (if FFf, EEs TFf)	High	High	High	High	High	High	High
9	EEs (if EEf TFf)	Reasonably High	Reasonably High	Reasonably High	High	Reasonably High	Reasonably High	High

Aggregation of experts judgment using the expert's weight and converted linguistic result to crisp number in Table 7. 5 the probability of each point from each experts can be seen in Table 10.11 which leads to the total probability of successful safety system in Table 10.12 Furthermore, using (7) the failure of each node also can be seen in Table 10.13

Table 10. 11: Aggregation of expert's judgement

Node	E1	E2	E3	E4	E5	E6	E7
1	0.1	0.1	0.065	0.065	0.11375	0.0875	0.07
2	0.05	0.05	0.04875	0.04875	0.0325	0.025	0.0125
3	0.05	0.05	0.0325	0.0325	0.01625	0.025	0.05
4	0.075	0.05	0.0325	0.04875	0.0325	0.025	0.07
5	0.05	0.025	0.0325	0.01625	0.01625	0.025	0.0125
6	0.15	0.175	0.0975	0.0975	0.11375	0.07	0.07
7	0.15	0.175	0.0975	0.11375	0.11375	0.07	0.07

8	0.15	0.15	0.0975	0.0975	0.0975	0.07	0.07
9	0.175	0.175	0.11375	0.0975	0.11375	0.0875	0.07

Table 10.12: Success and fail probability.

Node	1	2	3	4	5	6	7	8	9
Success	0.601	0.268	0.256	0.334	0.178	0.774	0.79	0.733	0.833
Fail	0.399	0.732	0.744	0.666	0.822	0.226	0.21	0.267	0.167

Step 4. Quantify every sequence leading to failure

An integral aspect of risk management is to understand not only the individual components of a system but also the sequences in which they interact. Particularly in the context of fire safety, understanding the sequences that lead to failure can provide insights into where interventions may be most effective.

By referring to Figure 10.16, four potential event sequences have been identified that may result in failure. These are defined below. The scenarios are summarised in Table 10.13, while their associated probabilities are detailed in Table 10.14:

- Failure1: This sequence begins with the successful identification of the type of fire (TFs), followed by early successful identification (EEs). However, it subsequently experiences a failure in firefighting (FFf) and evacuation & escape (EEf).
  Represented as: Failure1 = {TFs, EEs, FFf, EEf}.
- Failure 2: Here, after successfully identifying the type of fire (TFs), there are consecutive failures in both early identification and evacuation & escape (EEf, EEf).
  Represented as: Failure2 = {TFs, EEf, EEf}.
- Failure 3: This sequence involves a failure in the initial identification of the fire type (TFf), followed by early successful identification (EEs). However, subsequent stages see failures in firefighting (FFf) and evacuation & escape (EEf).
  Represented as: Failure3 = {TFf, EEs, FFf, EEf}.

- Failure 4: Initiating with a failure in identifying the type of fire (TFf), this sequence also experiences consecutive failures in early identification and evacuation & escape (EEf, EEf).

  Represented as: Failure4 = {TFf, EEf, EEf}.

Table 10. 12: Frequency per year for each failure scenario

Failure	Probability
Failure 1	0.0798
Failure 2	0.3616
Failure 3	0.0173
Failure 4	0.0151

<u>Step 5. Quantify the consequence of failures</u>

In fire safety management, when a system fails, it's essential to quantify the potential ramifications. A crucial metric in this regard is the probability of loss of life.

To evaluate this, we referenced the established scale in Table 7. 6. This scale provides a framework for assessing the likelihood of fatalities based on specific failure sequences.

Subject matter experts utilised this scale to offer their insights. They systematically evaluated each failure, determining the potential threat to human life if such a failure occurs. Their assessments have been documented in Table 10.14

Table 10. 13: Linguistic result from expert's judgement

	E1	E2	E3	E4	E5	E6	E7
Failure 1	Reasonably High	Reasonably High	Reasonably High	Reasonably High	Reasonably High	Reasonably High	Reasonably low
Failure 2	Reasonably High	Reasonably High	Reasonably High	Reasonably low	Reasonably High	Moderate	Reasonably low
Failure 3	Low	Reasonably low	Very low	Low	Reasonably low	Low	Very low
Failure 4	Reasonably low	Reasonably low	Low	Low	Reasonably low	Reasonably low	Low

By referring to Table 7. 6 to convert the linguistic term in Table 10.14 and the expert's weight, aggregation of expert's judgment is performed. Table 10.15 shows the result of loss of life possibilities for each failure.

Table 10. 14: Loss of life possibilities for each events scenario

	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**
Failure 1	0.05	0.05	0.0125	0.0125	0.05	0.05	0.05
Failure 2	0.06	0.06	0.025	0.025	0.06	0.06	0.06
Failure 3	0.005	0.006	0.00125	0.00125	0.006	0.006	0.002
Failure 4	0.006	0.006	0.0025	0.0025	0.006	0.006	0.002

<u>Step 6. Quantify the potential loss of life for existing conditions.</u>

A critical aspect of risk assessment in fire safety is understanding the potential repercussions in real-world conditions. For this step, our focus is on quantifying the potential loss of life, given the prevailing conditions of the safety system. To achieve this, we employed the equation represented by (11). This equation provides a structured methodology to translate failure sequences into tangible figures, representing the likelihood of fatalities. Upon applying this equation to each identified failure, we derived quantifiable metrics that detail the potential loss of life. The results of this rigorous quantification are presented in Table 10.16

Table 10. 15: Individual risk and potential loss of live in 1 year

Failure	**Probability**	**Frequency per year**	**Fatality**	**Individual Risk**	**Potential Loss of live**
Failure 1	0.0798	0.399	0.0878	0.0350322	0.210193
Failure 2	0.3616	1.808	0.0878	0.1587424	0.952454
Failure 3	0.0173	0.0865	0.0416	0.0035984	0.02159
Failure 4	0.0151	0.0755	0.0522	0.0039411	0.023647

10.9 Potential Loss of Life Calculation (RCOs)

For each risk control option (RCO), affected branch probabilities were updated and PLL recalculated to measure risk reduction. In our quest to mitigate fire hazards, we extensively studied various Risk Control Options (RCOs). Of note, RCO1 (Mobile Shear Cutting) has a distinct advantage: it is believed to eliminate the potential of a fire hazard. Thus, under the implementation of RCO1, the Potential Loss of Life (PLL) due to a fire hazard is assumed to be zero. However, for a holistic understanding and in the interest of thoroughness, we proceeded to analyse the other RCOs, namely RCO2 (Cleaning Process) and RCO3 (Fire Extinguisher). The results of these studies are delineated below:

1. Cleaning Process Analysis

Table 10.18 presents the probabilities of success and failure associated with the cleaning process. By analysing each point, we get insights into the reliability of this process as a control measure against fire hazards.

Table 10. 16: Success and fail probability for cleaning process

Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Success	0.165	0.268	0.256	0.334	0.178	0.774	0.79	0.733	0.833
Fail	0.835	0.732	0.744	0.666	0.822	0.226	0.21	0.267	0.167

Subsequently, Table 10.19 provides the frequency of failures per year, revealing the occurrences that might still pose a threat despite the cleaning process in place.

Table 10. 17: Frequency per year for each failure scenario - cleaning process

Failure	**Probability**
Failure 1	0.0022
Failure 2	0.0992
Failure 3	0.0362
Failure 4	0.0315

Finally, Table 10.20 offers a granular view, breaking down the individual risks and potential losses of life associated with each failure scenario.

Table 10. 18: Individual risk and potential loss of live in 1 year – cleaning process

	Probability		**Fatality**	**Individual Risk**	**Potential Loss of live**
Failure 1	0.0022	0.011	0.0878	0.0009658	0.005795
Failure 2	0.0992	0.496	0.0878	0.0435488	0.261293
Failure 3	0.0362	0.181	0.0416	0.0075296	0.045178
Failure 4	0.0315	0.1575	0.0522	0.0082215	0.049329

2. Fire Extinguisher Analysis

For the Fire Extinguisher, our assessment began with Table 10.21, which again offers a detailed view of the success and failure probabilities.

Table 10. 19: Success and fail probability – fire extinguisher

Point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Success	0.601	0.268	0.711	0.334	0.178	0.774	0.866	0.733	0.833
Fail	0.399	0.732	0.289	0.666	0.822	0.226	0.134	0.267	0.167

Table 10.22 then provides the yearly frequency of each failure scenario, offering insights into potential risks in the timeline of a year.

Table 10. 20: Frequency per year for each failure scenario – fire extinguisher

Failure	**Probability**
Failure 1	0.0310
Failure 2	0.3616
Failure 3	0.0111
Failure 4	0.0151

Lastly, Table 10.23 details the individual risks, fatalities, and potential loss of life over a year due to failures when relying on fire extinguishers.

Table 10. 21: Individual risk and potential loss of live in 1 year – fire extinguishers

	Probability	**Frequency per year**	**Fatality**	**Individual Risk**	**Potential Loss of live**
Failure 1	0.031	0.155	0.0878	0.013609	0.081654
Failure 2	0.3616	1.808	0.0878	0.1587424	0.952454
Failure 3	0.0111	0.0555	0.0416	0.0023088	0.013853
Failure 4	0.0151	0.0755	0.0522	0.0039411	0.023647

10.10 Comparative Analysis of Risk Reduction

The change in PLL (ΔPLL) is compared across RCOs and carried forward to the cost-benefit analysis, where higher ΔPLL indicates a more effective control. To compare and contrast the effectiveness of each RCO, Table 10.22 presents the reduction in potential loss of life for each method compared to existing conditions. This table serves as a decisive tool to inform our safety decisions, Optimising for the most significant reduction in potential hazards.

Table 10. 22: Reduction of potential loss of live in one year

Study case	**PLL**	**Delta PLL**
Existing condition	0.645044	-
Mobile shear	0	0.645044
Cleaning process	0.184761	0.460283
Fire extinguisher	0.586086	0.058958

Following the detailed analysis in Table 10.24, the significance of two metrics stands out: Potential Loss of Life (PLL) and the change in Potential Loss of Life (ΔPLL). The PLL metric offers insight into the expected fatalities within a specified timeframe under given conditions or interventions. Conversely, ΔPLL captures the difference or reduction in PLL when specific interventions or Risk Control Options (RCOs) are introduced. In the subsequent chapter, these metrics will be pivotal in the cost-benefit analysis. By quantifying and then weighing the reductions in potential fatalities (ΔPLL) against the costs of implementing each RCO, a comprehensive evaluation emerges that balances both human safety and economic considerations.

10.11 Chapter Summary

This chapter delved into the ship recycling processes at an Indonesian yard, emphasizing the identification and evaluation of associated risks. The processes of ship recycling were laid out clearly, drawing attention to potential dangers. By breaking down each recycling step, the related risks were identified. Using this detailed information, the chapter then assessed these risks to find the most concerning areas. Based on the findings, specific strategies were suggested to manage and reduce these risks. An important part of this analysis was the measurement of Potential Loss of Life (PLL) and the expected reductions (ΔPLL) from applying these strategies. The next chapter will take these results forward, focusing on the cost and benefits of implementing the proposed risk-reducing strategies, using a formal simulation method.

Chapter 11. Case Study on Employing Discrete Event Simulation in a Cost-Benefit Analysis Framework

11.1 Chapter Overview

This chapter focuses on the integration of discrete event simulation within the confines of a cost-benefit analysis framework. This examination emphasizes the significance of efficiency assessments, encapsulating both the refinement of existing process models and the inception of new ones. Subsequently, the chapter transitions to a detailed cost-benefit assessment, fastened by the GCAF and NCAF calculations, offering an in-depth exploration into the economic facets of ship recycling processes.

11.2 Efficiency Assessment through Discrete Event Simulation

In the assessment of complex systems, Discrete Event Simulation (DES) emerges as a powerful tool for evaluating efficiency. DES is used to be for wide applicability spans sectors like manufacturing, healthcare, transportation, computer science, and environmental planning as mentioned in chapter 6. For this study case, it will be reached through the steps below.

11.2.1 Developing the benchmark process model.

After understanding the process flow, the next step was the development of the current ship recycling discrete event simulation model in the ARENA Discrete Event Simulation software. Arena has been applied to evaluate different options in the case studies; performance of different layout alternatives, resource combinations (worker, cranes, transporters, polygrabs etc.), technology, alternative cutting technologies, and different plate sizes, have been implemented through simulation approach (Gunbeyaz, 2019).

In the previous chapter, the process flow which has been developed, will be utilised to develop the models in a simulation environment. The data needed to be collected to successfully run this model are the process time, resources and tool needed. The input data was taken from observation study and previous research. The time data was inputted in input analyser tool in ARENA and was used in each process model. The simulation output that used in this research is the total time process for each model and the number of optimise resource in further analysis with optQuest tool in ARENA.

The current process model aimed to present the existing situation as a benchmark. The ship recycling process simulation model was split into five main parts; Ship arrival and administration; preparation; cleaning and primary cutting; secondary cutting; and segregation. The input needed for this model included various resources such as process time and the number of resources from the real condition.

In the previous study, process model has been developed etc

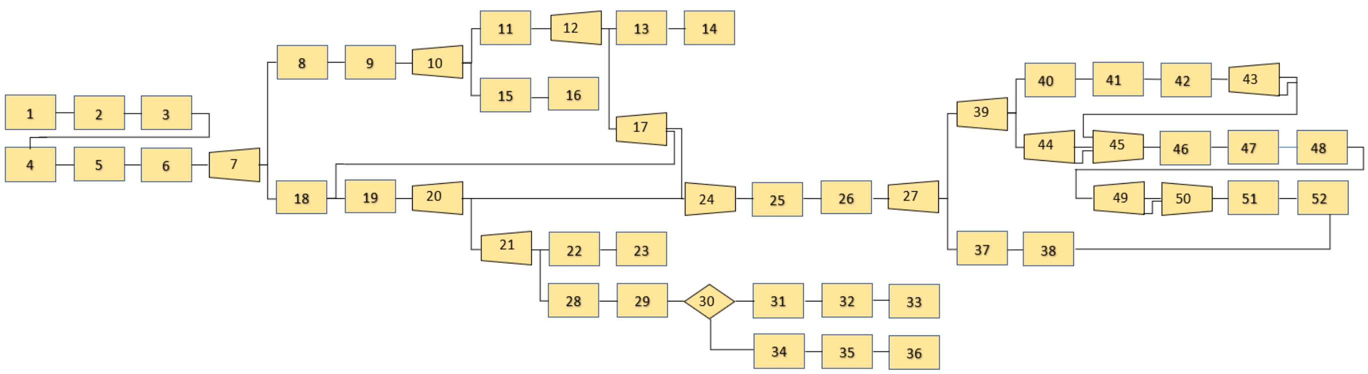


Figure 11. 1: Existing Indonesian ship recycling model in ARENA simulation

The table below will describe each process represented by the module in the ARENA simulation.

Table 11. 1: Module in the ARENA simulation

Step	No	Module Name	Module type	Properties
Ship arrival	1	Create ship	Create	Time between arrival: Random 30 days Entities per arrival 1, Max arrival 1.
	2	Record incoming ship	Record	Count, Number of Ship +1, No, Number of ships
Docking	3	Primary Zone A	Station	Name: Primary Zone A Type: station
	4	Securing the Ship	Process	Seize delay release Resources: Crane 1, Crane operator 1, helper 5, foreman 1

				Expression, minutes, value added NORM(14.4, 3.17)
	5	Ceremony	Process	Delay, Constant, 1 day, Non-value added
	6	Setting access to the ship	Process	Seize delay release Resources: Cutter 2, helper 3, foreman 1 Triangular, minutes, value added 20,30,40
Preparation	7	Parallel work 1	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	8	Delay of removal liquid waste	Hold	Scan for condition. Condition: removal of liquid waste.WIP == 0 && Primary cutting blocks on shore.WIP == 0 && cutting on ground.WIP == 0
	9	Removal of liquid waste	Process	Seize delay release Resources: helper 1, electric pump Uniform, hours, value added 1, 1.5
	10	Separate liquid waste	Separate	Duplicate original Percent cost to duplicate: 0 # of duplicate 1
	11	Discharge rest of fuel	Process	Seize delay release Resources: helper 2, Uniform, hours, value added

				40, 60
	12	Separate rest of fuel	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	13	Assign rest of fuel	assign	Attribute, material index 3 Entity type, rest of fuel
	14	Route to Zone D	route	Destination type: station Station mane: Zone D
	15	Assign the liquid waste	assign	Attribute, material index 2 Entity type, liquid waste
	16	Unprofessional disposal	Dispose	liquid waste Throw in the sea
	17	Parallel work 2	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	18	Delay of cleaning	Hold	Scan for condition Condition: Initial Cleaning.WIP == 0 && Primary cutting offshore.WIP == 0 Queue Hold for cleaning.Queue
	19	Initial cleaning	Process	Seize delay release Resources: helper 2, Uniform, minutes, value added (10, 20)
	20	Parallel work 3	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	21	Separate reuse material	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1

	22	Assign waste and hazmat	Assign	Attribute, material index 4 Entity type, waste and hazmat
	23	Unprofessional disposal waste and hazmat	Dispose	
	24	Combined activities	Batch	Permanent. Batch size 2. Rule. Any entity
	25	Hold for primary cutting	Hold	Scan for condition. Primary cutting blocks on shore.WIP == 0 && Initial Cleaning.WIP==0
Primary cutting	26	Primary cutting offshore	Process	Seize delay release Resources: Cutting tool 5, cutter 5 Expression, minutes, value added 10 + WEIB(23.6, 0.593)
	27	Separate logic 5	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	28	Transfer to storage	Process	Seize delay release Resources: helper 2, Triangular, minutes, value added (3.5,10, 18)
	29	Storage zone D	Station	Name: Storage zone D Type: station
	30	Decide reuse material	Decide	N-way condition Attribute, material index, ==, 1
	31	Rest of fuel Delay	Delay	Allocation: Other. 2 days

	32	Assign fuel	Assign	Attribute, material index 1 Entity type, reuse materials
	33	Rest of fuel leave from the yard	Dispose	
	34	Reuse material delay	Delay	Allocation: Other. 2 days
	35	Assign reuse material	Assign	Attribute, material index 1 Entity type, reuse materials
	36	Reuse material leave from the yard	Dispose	Terminates entity
	37	Remove machinery	Process	Seize delay release Resources: helper 2, Cutter 2, cutting tool 2 Triangular, minutes, value added 25, 30, 40
	38	Assign machinery	Assign	Attribute, material index 5 Entity type, machinery
	39	Separate logic 4	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	40	Pulling ship to the ground	Process	Seize delay release Resources: helper 2, crane 1, crane operator 1 Expression, minutes, value added NORM(14.4, 3.17)
	41	Securing a ship	Process	Seize delay release Resources: Foreman 1, helper 4. Expression, minutes, value added 14.5 + 16 * BETA(0.0382, 0.0471)

	42	Hold for primary cutting 2	Hold	Scan for condition. cutting on ground.WIP == 0 && Initial Cleaning.WIP==0
	43	Cutting on ground	Process	Seize delay release Resources: Cutting tool 5, cutter 5 Expression, minutes, value added 10 + EXPO(22.2)
	44	Separate logic cutting on shore	Separate	Duplicate original Percent cot to duplicate: 0 # Of duplicate 23
	45	Combined work 2	Adjustable batch	Permanent. Optimum Batch size 20. Maximum wait time 1 hours
	46	Transfer to the secondary zone	Process	Seize delay release Resources: Foreman 1, helper 4. Expression, minutes, value added 45.5 + 70 * BETA(0.531, 0.726)
	47	Secondary Zone B	Station	Name: Secondary Zone B Type: station
	48	Secondary cutting of blocks	Process	Seize delay release Resources: Cutting tool 5, cutter 5 Expression, minutes, value added 11 + WEIB(41.4, 0.7)
	49	Logical separation for plate number	Separate	Duplicate original Percent cot to duplicate: 0

				# of duplicate TRIA(15,20,30)
	50	Batch for loading to the trucks	Adjustable batch.	Permanent. Optimum batch size 5. Maximum wait time 1 days
	51	Loading to the truck	Process	Seize delay release Resources: Crane 1, helper 5, crane operator 1 Expression, minutes, value added 45.5 + 70 * BETA(0.531, 0.726)
	52	Steel leaves out	Dispose	Terminates entity

11.2.2 Developing the new process model

Having established benchmarks, this section focuses on enhancing the model by integrating a Risk Control option 1, specifically using the mechanical shear mechanism. We have devised a new ship recycling process model that employs a mobile shear as the cutting tool. This model has been meticulously developed using the ARENA Discrete Event Simulation software, as illustrated in Figure 11.2

The incorporation of the mechanical shear represents a pivotal enhancement, as it offers an innovative approach to ship recycling. The mobile shear, employed as the primary cutting tool, optimises the dismantling process by ensuring precision, safety, and efficiency.

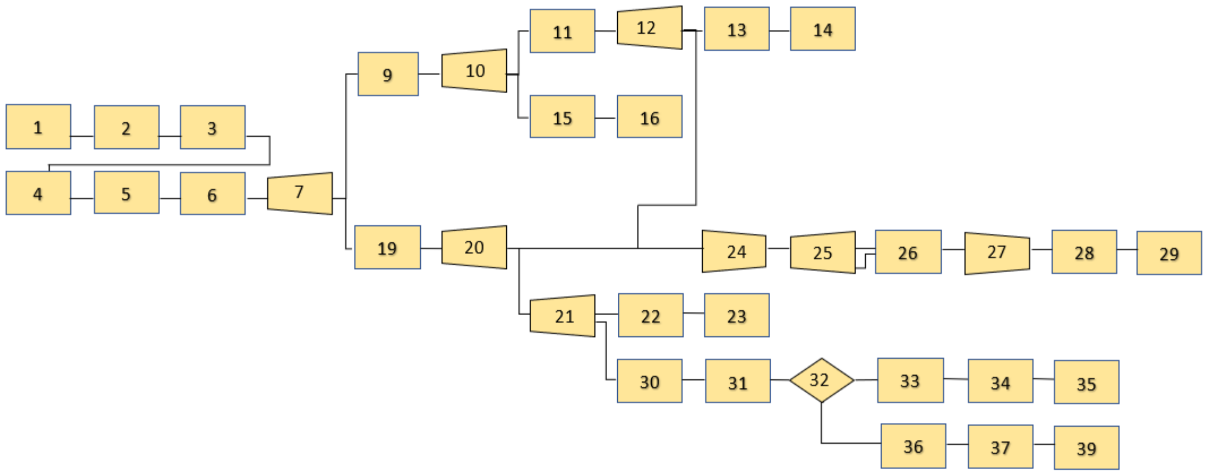


Figure 11. 2: Indonesian ship recycling model with Mobile shear as cutting tool in ARENA simulation.

The table below will describe each process represented by the module in the ARENA simulation.

Table 11. 2: Module in the ARENA simulation

Step	No	Module Name	Module type	Properties
Ship arrival	1	Create ship	Create	Time between arrival: Random 30 days Entities per arrival 1, Max arrival 1.
	2	Record incoming ship	Record	Count, Number of Ship +1, No, Number of ships
Docking	3	Primary Zone A	Station	Name: Primary Zone A Type: station
	4	Securing the Ship	Process	Seize delay release Resources: Crane 1, Crane operator 1, helper 5, foreman 1

				Expression, minutes, value added NORM(14.4, 3.17)
	5	Ceremony	Process	Delay CONSTANT, 1 DAYS, NON-VALUE ADDED
	6	Setting access to the ship	Process	Seize delay release Resources: Cutter 2, helper 3, foreman 1 Triangular, minutes, value added 20,30,40
Preparation	7	Parallel work 1	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	9	Removal of liquid waste	Process	Seize delay release Resources: helper 1, electric pump Uniform, hours, value added 1, 1.5
	10	Separate liquid waste	Separate	Duplicate original Percent cost to duplicate: 0 # of duplicate 1
	11	Discharge rest of fuel	Process	Seize delay release

				Resources: helper 2, Uniform, hours, value added 40, 60
	12	Separate rest of fuel	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	13	Assign rest of fuel	assign	Attribute, material index 3 Entity type, rest of fuel
	14	Route to Zone D	route	Destination type: station Station mane: Zone D
	15	Assign the liquid waste	assign	Attribute, material index 2 Entity type, liquid waste
	16	Unprofessional disposal	Dispose	liquid waste Throw in the sea
	19	Initial cleaning	Process	Seize delay release Resources: helper 2, Uniform, minutes, value added (10, 20)

	20	Parallel work 3	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	21	Separate reuse material	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	22	Assign waste and hazmat	Assign	Attribute, material index 4 Entity type, waste and hazmat
	23	Unprofessional disposal waste and hazmat	Dispose	Terminates entity
	24	Combined activities	Batch	Permanent. Batch size 2. Rule. Any entity
	25	Logical separate for cutting		Duplicate original Percent cot to duplicate: 0 # of duplicate 1
Primary cutting	26	Primary cutting mobile shear	Process	Seize delay release Resources: Cutting tool 5, cutter 5 Expression, minutes, value added

				10 + WEIB(23.6, 0.593)
	27	Separate logic 5	Separate	Duplicate original Percent cot to duplicate: 0 # of duplicate 1
	28	Loading to truck		Seize delay release Resources: Crane 1, helper 5, crane operator 1 Expression, minutes, value added 45.5 + 70 * BETA(0.531, 0.726)
	29	Steel leaves out	Dispose	Terminates entity
	30	Transfer to storage	Process	Seize delay release Resources: helper 2, Triangular, minutes, value added (3.5,10, 18)
	31	Storage zone D	Station	Name: Storage zone D Type: station
	32	Decide reuse material	Decide	N-way condition Attribute, material index, ==, 1

	33	Rest of fuel Delay	Delay	Allocation: Other. 2 days
	34	Assign fuel	Assign	Attribute, material index 1 Entity type, reuse materials
	35	Rest of fuel leave from the yard	Dispose	Terminates entity
	36	Reuse material delay	Delay	Allocation: Other. 2 days
	37	Assign reuse material	Assign	Attribute, material index 1 Entity type, reuse materials
	38	Reuse material leave from the yard	Dispose	Terminates entity

The use of mobile shear suggests a method optimised for rapid cutting and processing, often used in scrap yards or for demolition work. Its design and capabilities allow it to circumvent several processes required in the generic method.

- Securing a ship: Mobile shear operates in a manner where the material doesn't require additional stabilization steps. The design ensures the shear can grip and cut effectively without external securing.
- Hold for primary cutting & Hold for primary cutting 2: Mobile shear's efficient cutting capability allows it to commence operations immediately without awaiting other processes, thus rendering these holding steps unnecessary.
- Parallel Work (Multiple Steps): Mobile shear's streamlined and direct approach removes the need for simultaneous operations that would otherwise be conducted in parallel.
- Initial Cleaning: The mobile shear method integrates the cleaning process with the cutting, so there is no separate cleaning step.

- Separate Logic Steps: Mobile shear's primary purpose is to shear materials, so additional separations, like for different types of waste, are handled differently or at a subsequent stage, thus eliminating immediate separation logic.
- Pulling ship to the ground & securing a ship on ground: The mobile shear can operate in varied positions, making it unnecessary to reposition or re-secure the ship after initial processing.
- Cutting on Ground: Mobile shear performs cutting efficiently, reducing the need for separate ground cutting steps.
- Secondary Cutting of Blocks: Mobile shear performs primary cutting at such a level that it eliminates the need for secondary cutting. It cuts precisely and efficiently, allowing for fewer stages of material processing.
- Batch for loading to the trucks & Loading to the truck: The output from the mobile shear process is directly ready for loading, eliminating the batching or separate loading steps.

The mobile shear streamlines the ship recycling process by significantly reducing the number of necessary steps. Its design and functionality are suited for rapid and efficient processing, making several modules in the generic method redundant.

Furthermore, the detailed module outlined below is nested within the primary framework of cutting utilising a mobile shear, as showcased in Figure 11.3. This module elucidates the intricate steps and calculations essential to the mobile shear cutting process, ensuring its precision and efficiency

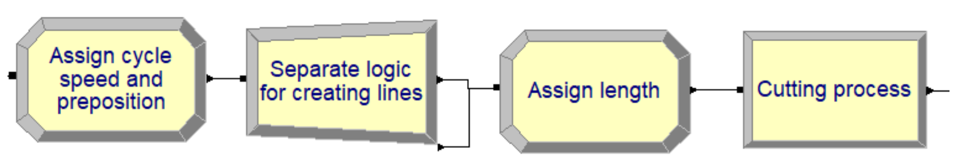


Figure 11. 3: Cutting process model with mobile shear

Table 11. 3: Module in the ARENA simulation

No	Module name	Module type	Properties
1	Assign cycle speed and preposition	Assign	Attribute, Preposition, TRIA (5, 10, 15)

			Attribute, cycle speed, 4
2	Separate logic for creating lines	Separate	Duplicate original Percent cost to duplicate: 0 # of duplicates: 5.5 + LOGN(15.5, 13)
3	Assign length	Assign	Attribute, Cutting length, TRIA(0.5, 1, 1.5)
4	Cutting process	Process	Seize Delay Release, Medium. Resource, Mobile shear, 1 Resource, Mobile shear operator, 1 Expression, seconds, value added Preposition + (Cutting length / cycle speed)

The mobile shear cutting process model provides a systematic approach to estimating cutting time and requirements. In the beginning, the "Assign cycle speed and preposition" module determines the shear's operational speed and the initial setup, using a triangular distribution to capture variability. This speed is pivotal for ensuing computations.

The subsequent module, "Separate logic for creating lines," manages the segmentation of the material. This segmentation is statistically determined using a log-normal distribution, which mirrors a more genuine representation of the spread of cut lines, emphasizing the likelihood around the mean.

The third step, embodied by the "Assign length" module, designates the length of each segment to be sheared. This determination leverages a triangular distribution to set boundaries for the segment length, ensuring the flexibility of the process within realistic parameters.

Conclusively, the "Cutting process" module evaluates the time essential for the shearing action. Here, the timing, denoted as t, is influenced by two core components: the prepositioning time p, ensuring the accuracy and efficiency of the impending cut, and the time it takes to shear, which is contingent on the cutting length l and cycle speed s. This relationship is mathematically encapsulated by the equation:

$$t(p,s,l)=p+l/s$$

This equation proficiently predicts the time needed for diverse cutting lengths, cycle speeds, and preposition durations. Hence, by integrating predetermined operational parameters with statistical distributions reflecting real-world variability, the model furnishes a structured method to estimate and enhance the mobile shear cutting process

11.2.3 Data Demonstration

The data demonstration focuses on the systematic collection, analysis, and application of key inputs to develop and validate the simulation models for ship recycling processes. Using ARENA Discrete Event Simulation software, this section outlines the data preparation steps and their integration into the models to ensure accuracy and reliability.

11.2.3.1 Data Collection

As mentioned before, the input data was gathered from multiple sources, including direct observations of ship recycling operations, prior research, and industry reports. Key parameters collected include:

- Process Times: Ranging from 1 to 60 minutes for various activities, such as initial cleaning (10–20 minutes) and liquid waste removal (1–1.5 hours).
- Resources: Workers (cutter and helper) (10), cutting tools (5), cranes (2), and other equipment essential for the recycling process.
- Material Flow: Handling between 5 to 10 entities per batch, based on real operational data.

- Probabilistic Distributions: Parameters such as Normal, Triangular, and Weibull distributions were used to model variations in operational tasks.

11.2.3.2 Data Analysis

The collected data was analysed using ARENA's **Input Analyser** to determine appropriate statistical distributions for each input variable:

- **Arrival Times**: Exponential distribution with an average interval of 30 days between ship arrivals.

- **Cutting Times**: Weibull distribution for primary cutting (23.6,0.593)(23.6, 0.593)(23.6,0.593) and secondary cutting (41.4,0.7)(41.4, 0.7)(41.4,0.7).

- **Preparation Tasks**: Triangular distribution ranging from 20 to 40 minutes, with a mode of 30 minutes.

11.2.3.3 Simulation Input

The processed data was organised into modules within ARENA, with a total of 52 modules representing the ship recycling process. Key activities modelled include:

- Ship Arrival and Docking: A single ship arrives every 30 days on average, with docking requiring resources such as 1 crane operator and 5 helpers.
- Cutting and Material Segregation: Modelled using Weibull distributions to capture complexity and variability.
- Waste Disposal: Tasks like liquid waste removal were modelled with Uniform distributions (1–1.5 hours).

11.2.3.4 Validation of Input Data

To ensure the reliability and accuracy of the simulation model, its outputs were validated against real-world operational data:

- **Total Process Time**: The baseline simulation model estimated a total processing time of **11.6 working days** per ship, based on an 8-hour workday. This closely aligns with the observed real-world processing time of **12 working days**, demonstrating the model’s ability to accurately replicate actual operational durations.

- **Resource Utilisation**: The simulated resource allocation, such as an 85% utilisation rate for cutting tools and cranes, was consistent with observed usage patterns, confirming the model's capability to reflect real-world resource demands accurately.

11.2.3.5 Simulation Output

The validated simulation produced the following key outputs:

- **Total Process Time**: For the baseline model, the average time was 300 minutes per ship. With the mobile shear, this was reduced to 150 minutes.

- **Resource Optimisation**: Labour requirements decreased from 10 workers to 5 workers per ship, reflecting improved efficiency.

- **Capacity Increase**: Annual recycling capacity doubled from 7 to 14 ships due to time savings.

This demonstration ensures that the simulation models are robust and reflect real-world conditions, providing a reliable foundation for further efficiency assessments and cost-benefit analyses. By leveraging statistical tools and validation techniques, the data supports meaningful insights into Optimising ship recycling operations.

11.2.4 Completion Time for Existing and New Processes

With the current resources, the yard can recycle 7 ships per year. Compare to cutting process with mobile shear, the time will be reduced half. With that time efficiency, the estimation of potential market of the ship that can be scrapped is 2x bigger than the existing condition now. It is estimated that the yard can recycle a maximum 14 ship per year.

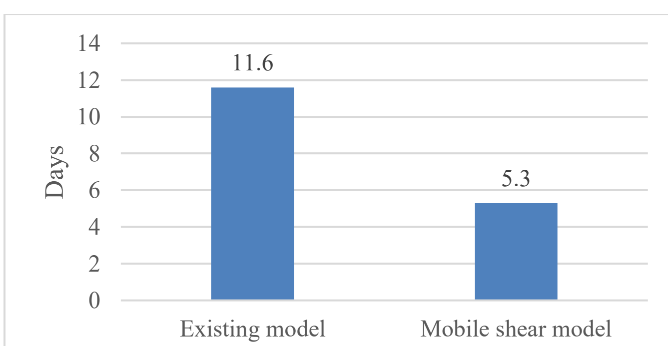


Figure 11. 4: Completion time (days)

Furthermore, additional profit can be projected. Assuming a consistent increase in the number of ships recycled due to efficiency improvements and a stable market demand, we can project the profits over the year If, for instance, each ship brings in a profit of $X, then recycling 7 ships yields a profit of 7X, with the improved efficiency allowing for the recycling of 14 ships annually, the profits would amount to 14X.

11.2.5 Resources Reduction

The adoption of the mechanical shear in the ship recycling process offers not only a time-efficient method but also introduces significant resource optimisation. One of the most apparent impacts is on labour requirements. Utilising this technology can effectively reduce the need for manual labour, directly influencing operational costs.

For instance, if a yard typically employs a team of 10 workers for the manual cutting process, the mechanical shear can potentially eliminate or reallocate these roles, leading to savings in terms of salaries, training, and related overheads. This does not only represent a direct reduction in costs but also mitigates potential risks and health hazards that workers might face in the manual dismantling process.

Furthermore, the reduced dependency on manual labour can ensure more predictable operational timelines, reducing variability and potential delays in the recycling processes.

11.3 Cost Benefit Assessment

We will primarily employ the Gross Cost of Averting a Fatality (GCAF) and the Net Cost of Averting a Fatality (NCAF) as our central evaluation tools as follows below.

11.3.1 GCAF calculation

In this case, cost benefit is calculated in 20 years, in-line with the lifetime of Risk Control 1 (Mobile shear). Total Potential Loss of Life (PLL) for existing condition and risk control options in 20 years, referring to the previous chapter, can be seen in table 11.1 below.

Table 11. 4: Total potential loss of life in 20 years

	Potential Loss of life in 20 years*	**PLL reduction in 20 years***	**Total reduction cost, in terms of safety (USD)**

Baseline PLL	17.8	-	
RCO1	0.000358	17.79	53. 39 million
RCO2	0.357903	17.44	52.39 million
RCO3	7.15806	10.64	31.92 million

*20 years is the lifetime of mobile shear as benchmark

Furthermore, the Net Present Value and GCAF of each risk control can be seen as below.

RCO1: Calculation of NPV and GCAF of Mobile Shear

Cost Estimation of Mobile Shear (USD)	
Allied-Gator MT® Series Multi-Tool model MTR 160 S	
Technical time: 20 years	
Purchasing Cost	300,000.00
Operational Cost	800,000.00
Training Cost	20,000.00
Maintenance Cost	200,000.00
Operator Cost	700,000.00
Total Cost:	2,020,000.00
Delta PLL	
NPV	537,478.97
PV0 (capital cost)	496,000.00
FV (Annual maintenance and operation cost)	200,000.00
Rate	0.06
Gross CAF	113,543.63
NPV	537,478.97
Delta PLL in 20 years	17.79

RCO2: Calculation of NPV and GCAF of Cleaning process

Total Cost:	**10,000.00**

Training Cost	5,000.00
Operational Cost	-
Helper salary (5)	4,800,000.00
Electricity	320,000.00
Delta PLL	
NPV	2,812,998.18
PV0 (capital cost)	5,000.00
FV (Annual maintenance and operation cost)	240,250.00
Rate	0.06
Gross CAF	161,295.77
NPV	2,812,998.18
Delta PLL in 20 years	17.44

RCO3: Calculation of NPV and GCAF of fire extinguishers

Total Cost:	**10,000.00**
Cost of 10 fire extinguisher	5,000.00
Training Cost	5,000.00
Maintenance cost	200.00
Delta PLL	
NPV	78,568.96
PV0 (capital cost)	5,000.00
FV (Annual maintenance and operation cost)	1,850.00
Rate	0.06
Gross CAF	7,384.30
NPV	78,568.96
Delta PLL in 20 years	10.64

The Figure 11.1 below shows that RCO3 (Providing fire extinguisher) is the most efficient solution according to the GCAF (USD) calculation. Continue with RCO1 (mobile shear as cutting machine), and RCO2 (De-coating process) in a row.

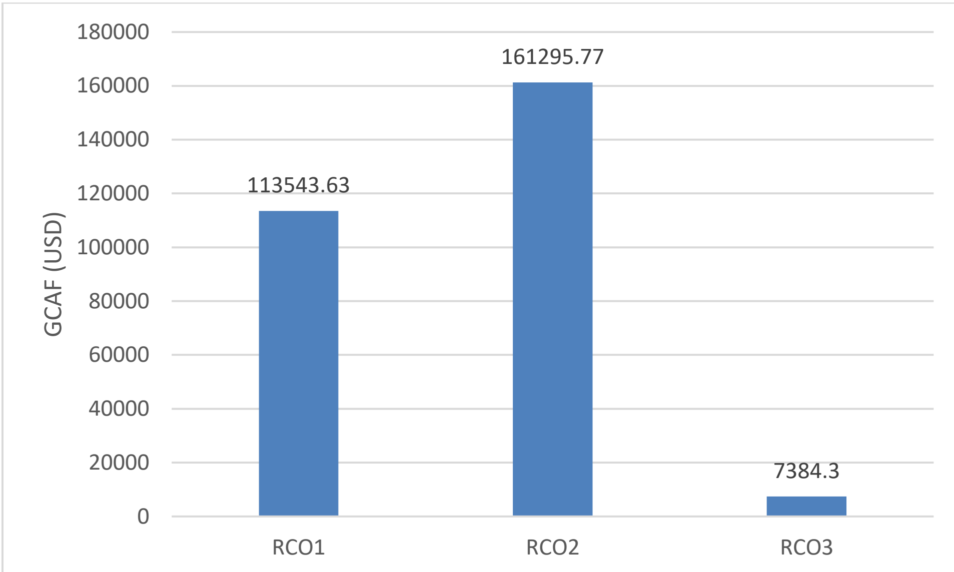


Figure 11. 5: GCAF calculation for each risk control options (USD)

11.3.2 NCAF calculation

In addition to labour cost savings, the adoption of the mechanical shear (RCO1) introduces significant efficiency gains in terms of increased capacity and reduced processing time. These benefits can be summarized as follows:

Table 11. 5: Additional benefit for each risk control option

Matrix	RCO1	RCO2	RCO3
Time Reduction	50% reduction (11.6 days to 5.8 days)	None	None
Capacity Increase	Capacity doubled from 7 ships/year to 14 ships/year	None	None
Labour Cost Savings	Reduction from 10 workers to 5 workers	None	None
Operational Cost Impact	Significantly reduced due to shorter time and fewer resources	None	None

The economic benefit of implementing the mechanical shear (RCO1) in the ship recycling yard was analysed based on two primary factors: labour cost savings and revenue increase due to enhanced capacity. These calculations were conducted over the operational lifespan of 20 years, utilising observed data from the ship recycling industry in Indonesia.

11.3.2.1 Labour cost savings:

- The adoption of the mechanical shear reduced the number of workers required per ship recycling process from 10 to 6, resulting in a workforce reduction of 4 workers. Based on actual salary data for shipyard workers in Indonesia, the average annual salary per worker is IDR 141,893,546. Over a 20-year period, the total labour cost savings were calculated as follows:
- Total Labour Cost Savings = Number of Workers Reduced × Annual Salary per Worker × Operational Period × Exchange Rate

  Total Labour Cost Savings = 4 × 141,893,546 × 20 × 0.000065 = USD 737,846.44
- This demonstrates a significant reduction in operational costs directly attributable to labour savings.

11.3.2.2 Revenue Increase Due to Enhanced Capacity

- The mechanical shear also increased the yard's annual recycling capacity from 7 ships to 14 ships, effectively doubling its throughput. This capacity enhancement resulted in the ability to process an additional 7 ships per year. The average profit generated per recycled ship, based on operational data, was IDR 1,000,000,000. Over a 20-year period, the total additional revenue was calculated as follows:
- Total Additional Revenue = Additional Ships per Year × Profit per Ship × Operational Period
- Total Additional Revenue = 7 × 1,000,000,000 × 20 = IDR 140,000,000,000 (9,100,000.00 USD)
- This additional revenue highlights the substantial financial benefit derived from increased capacity.

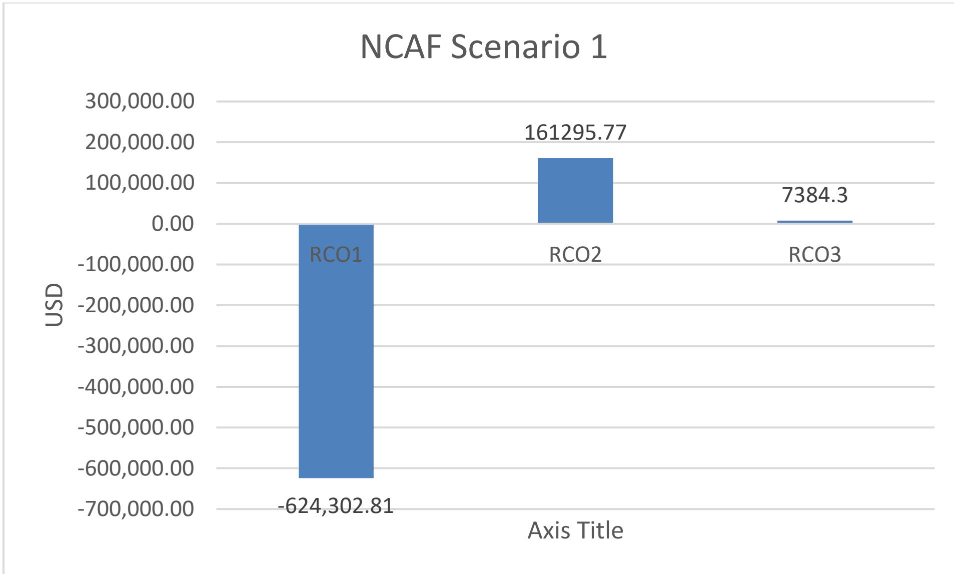
To evaluate the economic impact of the mechanical shear (RCO1), two NCAF values will be calculated. The first considers only the labour cost savings, while the second includes both labour cost savings and the revenue generated from increased capacity. This approach ensures a comprehensive understanding of the mechanical shear's financial benefits.

1. Scenario 1: NCAF Based Only on Labour Cost Savings
   This calculation focuses on the economic benefit derived solely from reducing the workforce required for ship recycling. The gross CAF remains constant at USD 113,543.63. The economic benefit, based on labour cost savings over a 20-year period, is USD 737,846.44. Using the NCAF formula, the NCAF value is calculated as the gross CAF minus the economic benefit from labour cost savings.

2. Scenario 2: NCAF Based on Labour Cost Savings + Revenue from Increased Capacity
   This calculation considers the full scope of the economic benefits, including both labour cost savings and the revenue generated from processing additional ships. The gross CAF remains USD 113,543.63. The total economic benefit combines USD 737,846.44 from labour savings and USD 9,100,000.00 from increased capacity, resulting in a total economic benefit of USD 9,837,846.44. The NCAF value is calculated as the gross CAF minus this total economic benefit. Furthermore, the NCAF for mobile shear can be calculated as below.

Gross CAF	113,543.63
NPV	78,568.96
Delta PLL in 20 years	17.79
Economy Benefit	10,022,308
NCAF-Scenario 1	-624,302.81 USD
NCAF-Scenario 2	-9,724,302.81 USD

The additional benefit in terms of efficiency plays important role in cost-benefit calculation in order to decide the best risk control, as a result, RCO1 (Mobile shear) become the most efficient options as shown in the graph below.



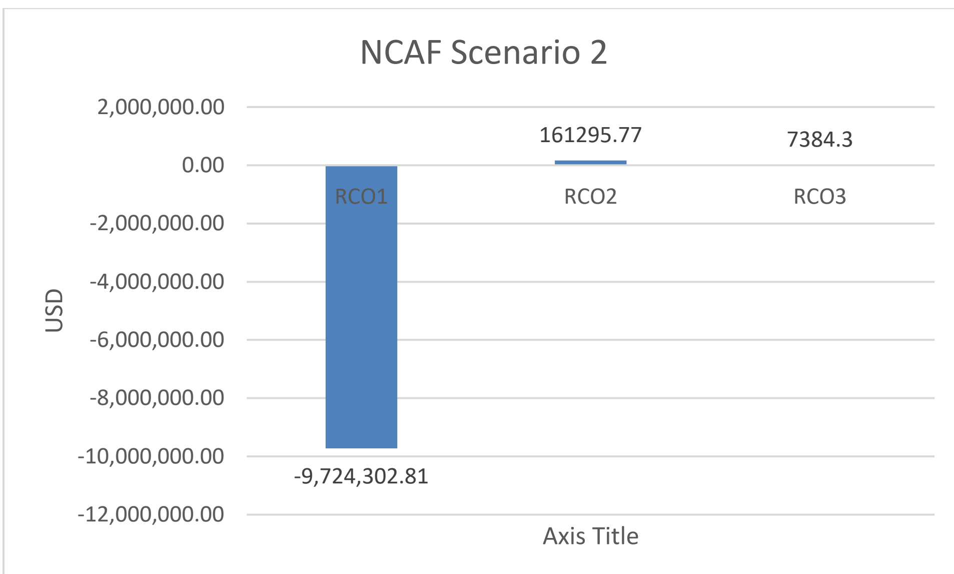


Figure 11. 6: NCAF calculation for each risk control options (USD)

The Net Cost of Averting a Fatality (NCAF) for RCO1, the mechanical shear, demonstrates its superior economic and safety value compared to other options. With a negative NCAF the mechanical shear not only offsets its implementation costs but also generates substantial economic benefits through labor cost savings and increased capacity. This indicates that the economic gains far exceed the costs of the intervention, making it the most cost-effective and impactful choice for reducing fatalities while enhancing operational efficiency in the ship recycling yard. By doubling capacity and halving processing time, RCO1 establishes itself as the optimal solution, achieving both economic and safety objectives.

11.4 Model validation and sensitivity analysis

The simulation model developed for this case study was validated to ensure that it accurately represents real-world ship recycling operations. Validation was conducted through three complementary methods: expert review, statistical comparison, and sensitivity analysis, as described in **Section 8.3.5**. Together, these steps confirm both the reliability and robustness of the model before applying it to evaluate risk control options.

11.4.1 Expert Review

Subject matter experts with direct experience in ship recycling were engaged to review the simulation model's structure, logic, and assumptions.

Their evaluation confirmed that:

- The process flow reflected the actual dismantling stages of ships in the yard.
- The resource allocations, including worker groups and machinery, were realistic.
- Hazard identification and risk control measures integrated into the model matched actual yard practices.

11.4.2 Statistical Validation

The simulation outputs were compared with actual yard operational data to confirm quantitative accuracy. Key performance indicators (KPIs) such as waiting time, and material recovery rate were used for comparison.

Metric	Real Yard Data	Simulation Output	% Difference
Material recovery rate (%)	94	92.5	1.6%
Waiting time for cutting team (h)	6	6.3	5.0%

The deviations between real-world data and simulation results were consistently below **10%**, indicating that the model faithfully replicates actual yard performance.

11.4.3 Sensitivity Analysis

A sensitivity analysis was conducted to test the **robustness** of the simulation model.
Key input parameters were varied systematically, and the resulting changes in outputs were observed to verify whether the model responded logically.

Parameter Adjusted	Original Value	Adjusted Value	Expected Effect	Observed Effect
Number of workers	40	50	Throughput should increase	Throughput increase by 12%
Ship arrival rate (ships/day)	2	3	Queue length should increase	Queue length increased by 18%
Processing time per section (min)	30	25	Waiting time should decrease	Waiting time decreased by 10%

The results matched expectations in every case, confirming that the model behaves logically and consistently under different operational scenarios.

11.5 Chapter Summary

This chapter examines the use of Discrete Event Simulation (DES) within a cost-benefit framework to enhance the efficiency of ship recycling. A benchmark model of the current process was created using ARENA software, incorporating key stages such as ship arrival, cutting, and segregation, based on observed data. Following this, a new process model introduced the use of a mobile shear cutting tool, which significantly streamlined operations by eliminating redundant steps and improving precision and safety.

The mobile shear reduced recycling times by half, enabling the yard to double its annual capacity to 14 ships. A cost-benefit analysis conducted over a 20-year period, using GCAF and NCAF metrics, demonstrated that the mobile shear is the most cost-effective solution, achieving substantial reductions in Potential Loss of Life (PLL) and operational costs. These findings highlight the value of combining DES with innovative tools to support safer, more efficient, and economically sustainable ship recycling processes.

Chapter 12. Discussion

12.1 Chapter Overview

This chapter provides general discussions about the research conducted in this thesis. First, achieved research aims and objectives were presented in Section 12.2 by explaining each specific objective given in Chapter 3. Following that, novelties and contributions to the literature in this PhD are provided in Section 12.3. Finally, a general discussion and primary results are presented in Section 12.4.

12.2 Discussion

The objectives listed in Chapter 3 were described as follows:

- *To conduct a thorough investigation of the hazards associated with ship recycling activities.*

The first objective aimed to conduct an exhaustive examination of the hazards present in ship recycling activities. This was achieved through several steps:

1. Identifying the Hazards (Chapter 2):
   The research commenced with an extensive literature review to compile a comprehensive list of potential hazards associated with ship recycling. These included physical injuries, chemical exposures, fire risks, explosions, and environmental contamination.
2. Field Study (Chapter 10):
   A detailed field study was conducted at various ship recycling yards, involving direct observations of hazardous conditions and practices. These visits provided real-time insights into the operational risks faced by workers, enabling an on-ground assessment of dangers in the ship recycling environment.
3. Workshops and Expert Interviews (Chapter 10):
   Workshops were organised with industry experts, workers, and safety professionals to discuss common hazards and effective mitigation strategies. These interactive sessions were crucial for understanding the practical challenges and best safety practices from those directly involved in the field.
4. Best Practices Guidelines (Chapter 7):

Based on international standards and best practices, guidelines were established to address identified hazards. These included safety protocols, proper handling and disposal of hazardous materials, and emergency response procedures, aimed at enhancing safety and operational efficiency in ship recycling.

5. Data Collection and Analysis (Chapter 10):

   Extensive data collection was conducted throughout the research, including statistical data on accidents, injuries, and hazardous events from various sources such as government reports, NGO publications, and direct field reports. This data was meticulously analysed to identify patterns and high-risk activities within ship recycling operations.

6. Development of a Hazard Inventory (Chapter 10):

   An inventory of hazards was developed, categorizing them based on frequency, severity, and potential impact on health and safety. This inventory served as a foundational tool for the subsequent risk assessment and mitigation strategies.

7. Validation and Refinement (Chapter 10):

   Initial findings were validated through additional field studies and consultations with industry stakeholders. Feedback from these sessions was used to refine the hazard identification and mitigation strategies, ensuring their practicality and effectiveness in real-world settings.

- *To undertake a comprehensive analysis of Health, Safety, and Environment (HSE) risks, incorporating meticulous data collection and extensive field studies.*

This objective focused on a thorough analysis of HSE risks, incorporating meticulous data collection and extensive field studies:

8. Detailed Risk Analysis (Chapter 5):

   The analysis involved extensive field studies, allowing for a granular understanding of the most hazardous aspects of ship recycling. This was supported by additional data from case studies, enhancing the reliability of the risk assessment.

9. Data Collection (Chapter 10):

   Data was collected on the frequency of hazardous events, supplemented by interviews with experts to gain deeper insights into the practical challenges faced in ship recycling yards. This comprehensive approach ensured a robust and detailed analysis of HSE risks.

10. Field Studies and Case Studies (Chapter 10):
    Multiple case studies were conducted, focusing on different aspects of the ship recycling process. These case studies provided empirical data and practical examples of risks and mitigation strategies, enriching the overall analysis.

- *To develop a robust risk assessment framework that aligns specifically with the intricacies of a ship recycling yard.*

The development of a risk assessment framework tailored to the intricacies of ship recycling yards was a critical objective:

11. Framework Development (Chapter 5 & 7):
    Chapters 5 and 7 laid the foundation for developing a structured risk-based approach tailored for ship recycling. This framework integrated insights from various sectors and offered a comparative analysis of different risk assessment methodologies.
12. Integration of Probability Calculations and Safety Analysis Tools (Chapter 5 & 7)
    The framework utilised renowned probability calculations and safety analysis tools to assess risks. This integration strengthened the robustness and applicability of the risk assessment framework in the context of ship recycling.

- *To perform a discrete-event simulation with the aim of Optimising productivity and cost in the ship recycling context.*

13. Utilising ARENA Software (Chapter 6 & 8):
    The ARENA software was employed to simulate different risk control measures, providing valuable insights into their economic impacts. This simulation enabled a comprehensive cost-benefit analysis, guiding informed decision-making for enhancing ship recycling operations.
14. Economic and Productivity Analysis (Chapter 8):
    The application of DES in a cost-benefit analysis framework provided a thorough evaluation of the financial and safety implications of various risk control options. This approach ensured that risk control measures were both effective and economically viable.

- *To validate the proposed framework through an empirical case study, with a specific focus on Indonesia's ship recycling sector.*

  Empirical validation of the proposed framework was conducted through case studies in Indonesian ship recycling yards:

15. Field Studies in Indonesia (Chapter 10 & 11):

    Chapters 10 and 11 presented case studies focusing on ship recycling yards in Indonesia. These studies highlighted the complex tasks involved, identified inherent risks, and proposed tailored risk control strategies.

16. Application of DES in Case Studies (Chapter 11):

    The application of DES in these case studies provided practical insights into the effectiveness of the risk assessment framework. This empirical validation demonstrated the framework's applicability and utility in real-world settings.

- *To acquire a detailed understanding of the Indonesian context, particularly its potential to bolster growth and development in the ship recycling industry.*

  The research explored the potential for growth and development in the Indonesian ship recycling industry:

17. Strategic Location Evaluation (Chapter 2 & 9):

    The study identified suitable locations for ship recycling yards in Indonesia, evaluating economic and safety factors to provide a strategic roadmap for establishing efficient and safe recycling operations.

18. Economic and Regulatory Analysis (Chapter 2 & 9):

    The research also analysed the economic implications and regulatory environment of the Indonesian ship recycling industry, highlighting opportunities for growth and development.

12.3 Novelties and Contributions

The innovative aspects uncovered during this PhD study are detailed below:

• Risk-Based Framework for Ship Recycling:

Within the author's comprehension, this research presents a pioneering approach in integrating risk and productivity tailored explicitly for ship recycling. Most studies have primarily addressed either risk or productivity; however, this work balances the two seamlessly. By identifying and delving into the hazards of ship recycling, and then proposing actionable risk control strategies, the research offers a tangible blueprint for safer and more efficient ship recycling operations. This systematic approach serves to benefit end-users by:

19. Facilitating safer recycling practices while Optimising productivity.
20. Helping stakeholders prioritize critical hazards and deploy efficient control measures.
21. Enabling a robust cost-benefit analysis, providing clear insights into the economic implications of different risk controls.
22. This unique methodology's advantages, some of which are highlighted in the chapters focusing on the Indonesian ship recycling context, include:
    8. Gaining in-depth insights into the local conditions, specifically the potential for the ship recycling industry's growth and development.
    9. Offering a structured framework to evaluate and decide upon the most suitable ship recycling locations.

• Innovative Use of DES for Cost-Benefit Analysis in Ship Recycling:

This PhD research appears to be among the first to exploit discrete event simulation, particularly using the ARENA software, to its fullest potential in the domain of ship recycling. Earlier endeavours may have touched upon this technique, but its exhaustive application, especially within a cost-benefit framework, remains a novelty. The study not only employs DES to grasp the intricacies of ship recycling but also seamlessly integrates it into a robust cost-benefit analysis mechanism. The research's novel applications of DES manifest in the following avenues:

- Identification of bottlenecks in the recycling process and the formulation of optimisation strategies.
- Comprehensive assessment of the economic ramifications of different risk control strategies, shedding light on both potential benefits and challenges.
- Enabling a deep dive into the nuances of the ship recycling process through the detailed exposition of DES in ARENA software, paving the way for informed, evidence-backed decision-making.

Further notable contributions of this research span:

- A complete examination of the Indonesian ship recycling yards, plugging knowledge gaps and offering a broad view of opportunities and barriers.
- The combination of hybrid decision-making tools in determining the most promising locations for ship recycling yard establishment.
- The empirical evidence of the research's framework through an in-depth case study, strengthening its practical viability and effectiveness.
- Collectively, these research innovations, as articulated across the chapters, deepen, and broaden the comprehension of ship recycling, emphasizing risk, productivity, and regional specificities.

12.4 Practical Use of the Framework

The ship recycling industry, with its intricate operations and multifaceted challenges, necessitates a holistic approach that is firmly rooted in academic rigor while being pragmatically applicable. This section elucidates the practical implications of the Risk-Based Ship Recycling Yard Improvement Framework, offering a guide on its integration into the complex realm of ship recycling.

Chapter 7 - Comprehensive Risk Analysis:

The seventh chapter provides a foundational understanding by presenting a detailed roadmap for stakeholders. Moving beyond mere hazard identification, it ventures into an in-depth risk analysis, identifying the risks with the most significant impact and their potential repercussions. This structured approach allows stakeholders to foresee challenges, paving the way for strategic risk control measures.

Chapter 8 - Operational Optimisation:

Building upon the foundation set by Chapter 7, the eighth chapter introduces the dynamism of Discrete Event Simulation (DES) via the ARENA software. Here, stakeholders gain an instrumental tool, allowing them to simulate diverse risk control scenarios. It translates safety initiatives into measurable financial outcomes, ensuring a harmony between compliance and economic pragmatism.

As we transition from the core framework's exposition in the aforementioned chapters, it's essential to understand its broader implications, not just in terms of safety but its far-reaching effects on sustainability, training, and financial viability.

1. Sustainability and Reputation Building:
   In today's global landscape, sustainable practices are not just a trend but a core business imperative. The framework accentuates an environmentally-responsible approach to ship recycling, ensuring alignment with global standards. More than just compliance, this positions the yard as a vanguard of sustainable operations, thereby enhancing its reputation and trustworthiness among stakeholders.

2. Flexibility for Future Needs:
   Change is the only constant in industries like ship recycling. This framework, while thorough, is not rigid. Designed with adaptability at its core, it can evolve to address new risks or shifts in operational practices, ensuring it remains relevant amidst industry evolution.

3. Evidence-Based Decision Making:
   Decision-making, to be effective, must be anchored in data. The framework underscores this by leveraging DES, affirming that risk control strategies are evidence-backed. Such a methodical approach reinforces stakeholder confidence and elevates operational transparency.

4. Skill Enhancement and Training:
   With clarity on risks comes the opportunity for targeted training. The framework, in spotlighting specific risks, provides the blueprint for employee education on these challenges and their mitigation techniques. This not only elevates efficiency but substantially reduces potential threats, culminating in a safer working environment.
5. Economic Implications:
   The financial dimension is pivotal, especially in sectors as capital-intensive as ship recycling. Through its cost-benefit analysis using ARENA, the framework paints a clear

picture of the financial implications of safety initiatives, ensuring they are as economically viable as they are effective.

12.5 Limitations

Every research effort, no matter how meticulously planned and executed, is bound to have certain constraints that might affect its scope, applicability, or generalizability. Recognizing these limitations not only ensures the authenticity and humility of the research but also offers a roadmap for future studies, highlighting areas that may need further exploration or a different methodological approach. In this section, we aim to address some of the intrinsic limitations of the current study on ship recycling practices, shedding light on potential areas of caution while interpreting the findings. By acknowledging these limitations, it is hoped that the research's results are considered within the appropriate context, ensuring meaningful and relevant applications.

1. Data Reliance

   For the studies case, the research heavily relies on data obtained from specific ship recycling yards, predominantly from Indonesian contexts. While this provides a detailed insight into the processes and challenges of these yards, it may not necessarily be representative of ship recycling practices globally. Different countries and regions may have distinct operational, regulatory, and cultural nuances that could affect outcomes.

2. Time Constraints

   The research was conducted within a specific timeframe, and thus, the findings represent a snapshot of the ship recycling industry during this period. As the industry is dynamic, with evolving technologies and regulations, some findings might become outdated as newer methods and practices emerge.

3. Scope of Assessment Tools

   While the Discrete Event Simulation (DES) using ARENA software offers valuable insights, it's worth noting that any simulation is based on specific assumptions and parameters. Variations in real-world scenarios or any unforeseen events could produce outcomes different from those predicted by the DES.

4. Stakeholder Engagement

   The research focuses predominantly on the operational and risk management aspects of ship recycling. While stakeholder opinions, especially from workers and environmental agencies, were considered, there might be broader socio-political or economic perspectives that were not deeply explored.

5. External Factors

   The research, although comprehensive, could not account for all external factors like global economic downturns, pandemics, or major policy shifts, which could influence ship recycling practices and the viability of proposed risk control measures.

This comprehensive section acknowledges the inherent limitations in the research and sets the stage for further studies or discussions in this domain.

12.6 Future Recommendations

Given the findings and conclusions of this research, several forward-looking recommendations are presented to further enhance the ship recycling industry's efficacy and sustainability.

- Holistic Environmental Framework: It is crucial to develop a comprehensive environmental framework tailored for the ship recycling industry. As global environmental concerns mount, integrating sustainable practices can not only mitigate ecological impact but also provide the industry with a competitive advantage in compliance with international standards.
- Human-Cantered Recycling Approaches: Ship recycling is not just about the ships; it's about the people involved. A human-centric approach should be adopted, prioritizing worker safety, training, and well-being. Advanced training modules focused on safety protocols, environmental protection measures, and emergency response can significantly reduce the potential for human error and casualties.
- Data-Driven Decision Making: With the findings highlighting certain data constraints, future endeavours should emphasize developing a robust ship recycling data repository. This can aid in more accurate simulations, decision-making, and identification of optimisation opportunities.

- Integration of Ship Design, Build, and Recycling Yards: It's imperative to consider the ship's entire lifecycle, from design to decommissioning. By integrating the processes and knowledge exchanges between the ship design teams, building yards, and recycling yards, a more sustainable model can be developed.

12.7 Chapter Summary

This chapter provides an overview of the research aims and objectives achieved, accompanied by a broad discourse on the constraints, presumptions, and obstacles faced throughout the PhD reviews. Novel ideas and notable contributions have also been distinctly emphasized.

Chapter 13. Conclusion

13.1 Chapter Overview

This chapter presents the findings from the research undertaken during this PhD and suggests potential directions for future research that could be explored as subsequent opportunities.

13.2 Conclusion

This PhD research presents a comprehensive investigation into the complexities of ship recycling, addressing a critical and underexplored area in maritime risk management. Despite the scale and significance of the maritime industry, there remains a notable gap in the literature when it comes to integrated risk assessment, economic evaluation, and environmental accountability within ship recycling operations. This PhD bridges that gap by proposing a novel three-step methodology, which consists of hazard identification, risk quantification using event tree analysis, and cost-benefit evaluation through GCAF and NCAF metrics. The framework is designed not only to contribute theoretically but also to offer practical decision-support tools for industry professionals and regulators.

The research draws on and builds upon foundational methodologies established in the fields of process safety and risk assessment, such as those outlined by the Centre for Chemical Process Safety (CCPS) and IEC 61882. These established practices have been adapted and refined to suit the operational realities and regulatory challenges specific to ship recycling. Additionally, prior works by Akyuz, Celik, and others provided the initial platform on which this study expands, particularly in relation to safety-critical activities within the maritime sector.

Chapter 7 offers a detailed analysis of hazard identification within ship recycling yards, grounded in empirical data collection and site observations. These insights enabled the development of a risk assessment model specifically tailored to the unique context of ship dismantling. This research moves beyond conventional applications by contextualising these frameworks within the Indonesian ship recycling industry, an area with both high potential and significant regulatory challenges.

One of the key contributions of this study is the application of discrete-event simulation (DES) to ship recycling operations, an approach not previously applied in this field. Chapters 6 and 8 demonstrate how simulation modelling, particularly using the ARENA software, can support productivity optimisation and cost evaluation while accounting for risk control interventions. The integration of DES with risk and economic analysis enables a more comprehensive understanding of how different mitigation strategies impact operational and financial performance.

Moreover, the research introduces a hybrid decision-support approach for selecting optimal ship recycling yard locations. By evaluating seven strategic sites in Indonesia based on environmental, socio-economic, and logistical factors, the study offers a practical framework for policy-makers and investors to guide infrastructure development and policy interventions in the sector.

The focus on Indonesia is particularly significant. Chapters 2 and 9 highlight the gap between the country's current ship recycling practices and its broader maritime ambitions. While the potential for economic growth through ship recycling is clear, it must be matched with improvements in environmental protection and worker safety. This research provides an evidence-based foundation to support that transition.

In conclusion, this PhD makes a distinctive contribution by integrating risk assessment techniques, simulation modelling, and economic evaluation into a unified framework tailored for ship recycling. It presents a methodology that is informed by international standards, validated through fieldwork, and applied in a national context where improvements are both necessary and feasible. The work advances academic discourse and, more importantly, provides stakeholders in Indonesia and beyond with actionable tools to enhance the safety, efficiency, and sustainability of ship recycling practices.

13.3 Chapter Summary

This chapter collects the comprehensive research journey undertaken throughout the study, highlighting key insights from each segment. From assessing ship recycling hazards to devising an industry-specific risk framework, the thoroughness and empirical dedication of the study stand out. The use of discrete-event simulation showcases modern methodology, while the focus on Indonesia offers real-world contextual relevance. In essence, this summary underscores the study's academic depth and its practical impact on the ship recycling industry.

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APPENDIX 1: Mapping Studies for Ship Recycling Literature Review

	Authors	Keywords/ indexing	Law, social & Policy	Economic Analysis/ Impact	Health & Safety	Environmental impact and waste management	Process Analysis/ best practice	Design for Recycle	Process Optimisation/ yard design
1	Islam and Hossain, 1986	-				x			
2	Zhijie, 1988	-				x			
5	Andersen et al., 2000	Ship decommissioning, Bangladesh, Chittagong, Recycling, Safety, Health, Environment (SHE)		x	x	x	x		
6	Andersen, 2001	-		x	x		x		
7	Creese and Sibal, 2001	-		x					
8	GREENPEACE, 2001	greenpeace, asbestos, toxics, ship breaking, asia	x	x	x	x			

9	GREENPEACE, 2001a	greenpeace, asia, toxics, ship breaking	x	x	x	x			
10	Tewari et al., 2001	heavy metals, microbial contamination, petroleum hydrocarbons, sewage, phytoplankton, zooplankton, ship scrapping industry				x			
11	Mattorano et al., 2001	-			x				
12	Creese et al., 2002	-		x					
13	FIDH, 2002	-	x		x	x			
14	GREENPEACE, 2002	-	x	x	x	x			
15	ILO, 2003	metalworking industry, occupational safety and health, environmental degradation	x		x	x	x		x

16	Reddy et al., 2003a	Alang–Sosiya, Ship scrapping yard, Solid waste, Oiled sponge, Textile waste, Wood pieces				x			
17	Stuer-Lauridsen et al., 2003	-	x	x	x	x	x		
19	Paul, 2004, Reddy et al., 2004a	Alang–Sosiya, Mahuva, Intertidal sediments, Metal contamination, Bulk fraction, Fine fraction				x			
20	Reddy et al., 2004b	Alang-Sosiya, DuLong's equation, Proximate and ultimate analysis, Ship scrapping, Waste to energy and energy potential				x			

21	Ahluwalia and Govindarajulu, 2005	-		x					x
22	Dimakopoulos, 2005	-	x						
23	ECORYS, 2005	-	x	x					
24	Mashreque, 2005	-	x		x	x			
25	Reddy et al., 2005b	Petroleum hydrocarbons, Heavy metal, Seasonal effects, Ship scrapping yard, Alang–Sosiya, Gulf of Cambay				x			
26	Reddy et al., 2005a	Regression analysis, Solids, Marine vehicles, Oil insulation, Plastic insulation, Waste materials, Glass, Wool, Cotton, Rubber				x			

27	Adamides et al., 2006	collaborative indirect process technology, lean and green management, ship dismantling						x	x
28	Ahluwalia and Grover, 2006	-			x	x	x		x
29	Alkaner et al., 2006a	-							x
30	Alkaner et al., 2006b	-						x	
31	Asolekar, 2006	Ship dismantling, ship breaking, ship scrapping, India, Alang, solid wastes, hazardous wastes, recyclings				x			
32	Ayvatoglu, 2006	-	x	x	x	x			
33	Bailey, 2006	-	x		x	x	x		x

34	Chaturvedi and Asolekar, 2006	-				x			
35	Gramann, 2006	-						x	
36	Hedlund-Astrom and Luttropp, 2006	-					x		
37	Hossain and Islam, 2006	-	x	x	x	x	x		
38	Karpowicz and Bruce, 2006	-							x
39	Kinigalakis and Karling, 2006	-							x
40	Kostopoulos et al., 2006	-					x		
41	Koumanakos et al., 2006	-							x
42	Mahindrakar and Asolekar, 2006	-				x			

44	Reddy et al., 2006	Alang-Sosiya, ship-breaking yard, small plastics, accumulation, intertidal sediments, microscopic fragmentation, FT-IR, SEM				x			
45	Stuer-Lauridsen and Ringgaard, 2006	Ship recycling, Hazardous waste, Basel Convention	x						
46	Vedeler, 2006	-						x	
47	Watkinson, 2006	-	x						
48	Watkinson and Wingfield, 2006	-	x						

49	Amin and Billah, 2007	nvironmental degradation, environmental impact, environmental impact, assessment, environmental policy, intertidal environment, marine ecosystem, soil pollution, sustainable development				x			
50	Basha et al., 2007	Alang-Sosiya, enrichment factor factor analysis Gopnath, suspended particulate matter				x			
51	Dilok, 2007	-						x	
52	Dodds, 2007	-	x	x	x	x			
53	Enger, 2007	-	x						

54	Rousmaniere and Raj, 2007	ship recycling, ship scrapping, shipbreaking, asbestos, Alang, Bangladesh, Mumbai, India, Basel Convention, Greenpeace; International Labour Organisation, International Maritime Organisation, International Metalworkers Federation			x	x			
55	Stuer-Lauridsen et al., 2007	-	x	x	x	x			
56	Andersen, 2008	-			x	x	x		
57	Charalambia Pylarinou et al., 2008	-							x
58	FIDH et al., 2008	-	x		x				

59	Stuer-Lauridsen et al., 2008	-	x		x				
60	Hossain et al., 2008	ship scrapping, toxic chemicals, health hazards, accidents and casualties, medical, facility, low waged labourers.			x				
61	Kinigalakis and Lindvall, 2008	-	x		x	x			
62	Knapp et al., 2008	Recycling of ships, Ship scrapping, Ship demolition, Probability of scrapping, International convention on ship recycling, Econometric modelling, Binary logistic regression		x					

63	Lightburn and Townsend, 2008	-		x			x		
64	(Mahindrakar et al., 2008)	-				x			
65	McKenna and Das, 2008	-	x	x	x		x		
66	Melton, 2008	-			x				
68	Moen, 2008	Shipbreaking, Basel Convention, Illegal traffic, Toxic ships	x						
69	Neser e al., 2008	Shipbreaking, Aliağa, Environment, Pollution, Hazardous wastes, Occupational health, Working safety, Basel Convention, Green recycling	x	x	x	x			
70	Neser and Unsalan, 2008	-				x			

71	Sivaprasad et al., 2008	-						x	
72	Sonak et al., 2008	Basel Convention, Developing countries, Equity, Hazardous waste	x						
73	Sundelin, 2008	-	x						
74	Tiwankar et al., 2008b	-				x			
75	Bhattacharjee, 2009	Basel Convention, Ship Recycling	x						
76	Karim, 2009	-	x		x				
77	Kumar, 2009	-			x	x	x		
78	Milieu&COWI, 2009	-	x	x					
79	NGO Ship Breaking Platform, 2009	-	x	x	x	x	x		
80	Ormond, 2009	-							
81	Pylarinou et al., 2009	-							x
82	Salim, 2009	-			x	x			

83	Abdullah et al., 2010	beach breaking, ship recycling, environment monitoring; coastal pollution, remote sensing			x	x			
84	Chang et al., 2010	Ship recycling, Marine environmental protection, International Maritime Organisation	x						
85	Demaria, 2010	Toxic waste management, Cost shifting, Material flows, Environmentalism of the poor, Environmental justice			x	x			
86	Deshpande et al., 2010	-					x		

87	Gregson et al., 2010	Follow the thing, Waste, Value chains, Ships, Furniture, Consumption, Bangladesh		x		x			
88	Hossain and Rahman, 2010	-				x			
89	Hossain et al., 2010	Shipbreaking Yards, HPGe Detector, Radionuclides, Activity Concentrations, Dose Rates, Radium				x			
90	NGO, 2010	-	x	x	x	x	x		
91	OSHA, 2010	-			x	x	x		
92	Sarraf et al., 2010	-		x	x	x			
93	Sivaprasad, 2010	-					x		

94	Courtice et al., 2011	Asbestos, Asbestos related disease, Bangladesh, Policy, Ship breaking			x				
95	Hossain, 2011	-		x	x	x	x		
96	LR, 2011	-						x	
97	NGO Ship Breaking Platform, 2011	-	x	x	x	x	x		
98	Deshpande et al., 2012	Ship dismantling, Ship breaking, Heavy metals, Worker exposure, Marine pollution, Air pollution			x				
99	Dhar et al., 2012	Biodegradation, Fungi, Petroleum hydrocarbon				x			
100	Formount and Pavasovic, 2012	-	x	x	x	x			

102	McKenna et al., 2012	ship recycling, environmentally friendly ship, naval architechture, Naval architecture. Shipbuilding. Marine engineering, Automotive Engineering, Mechanical Engineering, Environmental Engineering						x	
103	Neşer et al., 2012b	Ship recycling, Metal pollution, Sediments enrichment factor, Sediment quality guidelines, Aliağa Bay				x			

104	Neşer et al., 2012a	Ship recycling, Polycyclic aromatic hydrocarbons, Aliphatic hydrocarbons, Sediment quality guidelines, Aliaga Bay				x			
105	NGO Ship Breaking Platform, 2012a	-	x	x	x	x	x		
106	NGO Ship Breaking Platform, 2012b	-	x	x	x	x	x		
107	Ormond, 2012	-	x						
108	Pasha et al., 2012a	Dismantle, EIA, SBRI, Sustainable				x			
109	PROFUNDO, 2012	-	x						
110	Shameem, 2012	-	x	x	x	x	x		
111	Shimizu et al., 2012b	Afloat Method, Pilot Model, Ship Recycling, Water-					x		

		Jet Cutting							
112	Siddiquee et al., 2012	Trace metal affected area control site heavy metal alarming stage ship breaking area				x			
113	Sivaprasad et al., 2012	-						x	
114	URANO, 2012a	beaching, Japan, safe and environmentally sound, ship recycling, the Basel Convention, the Hong Kong Convention.	x				x		
115	Watkinson, 2012	-	x						

116	Welaya et al., 2012	Ship recycling, Ship scrapping, Marine environment protection, Ship breaking yard, Fuzzy logic approach	x				x		x
117	Zakaria et al., 2012	Ship recycling, ship dismantling, safety, safety hazards, environmental hazards		x	x	x			
118	Abdullah et al., 2013	Beach breaking, Ship recycling, Coastal management, Environment monitoring, Pollution, Remote sensing				x			
119	O. Arslan et al., 2013	Recycling, ship dismantling, training			x				

120	O. Arslan et al., 2013	Ship dismantling, ShipDIGEST, safety			x				
121	Cameron-Dow, 2013	Ship recycling, scrapping, Hong Kong Convention, Basel Convention	x						
122	Deshpande et al., 2013a	Appropriate technology, heavy metals, occupational safety, policy, risk assessment, ship breaking, ship recycling, worker exposure			x				
123	Deshpande et al., 2013b	-					x		
124	Hahladakis et al., 2013	Recycling, Ship, WEEE, Heavy metals, Simulation reacto				x			
125	Hasan et al., 2013	Trace metals, Pollution, Ship breaking, Sitakund Upazilla, Chittagong				x			

126	Hiremath et al., 2013a	Health, safety and environment, occupational safety, fault-tree analysis, what-if-analysis, ship breaking, ship recycling, integrated risk assessment			x				
127	Hiremath et al., 2013b	Ship recycling plan, oil tanker ship, IMO Guidelines, Inventory, Hazardous materials, Occupational safety, ship breaking					x		
128	Jain et al., 2013	Hong Kong Convention, IMO, Ship breaking, Ship recycling	x						
129	Jan Willem van Gelder et al., 2013	-	x	x					

130	Källmar et al., 2013	Ecodesign, DFE, Ship industry, Ship recycling, ISO14006, POEMS, LEAP						x	
131	Kurt et al., 2013	Accident investigation, occupational health and safety, ship dismantling			x				
132	Kusumaningdyah et al., 2013	-		x					
133	LITEHAUZ, 2013	-					x		
134	S. A. McKenna et al., 2013	shipDIGEST, ship dismantling, vocational education			x				
137	Mohammad, 2013	-			x	x			
138	Muhibbullah, 2013	Ship breaking, Hazards, Vulnerability, Sitakunda, Bangladesh			x				

139	Neser et al., 2013	-				x				
140	NGO Ship Breaking Platform, 2013a	-	x	x	x	x	x			
141	NGO Ship Breaking Platform, 2013b	-	x	x	x	x	x			
142	Pandey et al., 2013	Green passport, Hong Kong Convention, Inventory of Hazardous Materials, health and Safety, International Maritime Organisation, Hazardous Waste, Ship Recycling, Ship Recycling Facility Plan, Ship Recycling Plan	x							

143	Rai and Baumler, 2013	Basel Convention, Hong Kong Convention, Ship recycling	x						
144	Sivaprasad and Nandakumar, 2013	-						x	
145	(Tunarli and Fet, 2013)	Ship recycling, Aliaga, stakeholders, Greenpeace, Turkey	x						
146	(Vuori, 2013)	ship dismantling, ship recycling, environmental impact	x		x	x			
147	(Watkinson, 2013)	-	x						

150	(Hiremath et al., 2014)	Ecological Engineering, EcoIndustrial Networking, Industrial Ecology, Ship Recycling, Beaching method, Ship Dismantling, Health Safety and Environment, Hazardous Wastes Management			x	x			
151	(Jain et al., 2014)	-						x	
152	(Jobaid et al., 2014)	Ship Breaking, Existing laws, safety of workers, Environmental hazards, Child labour.	x	x		x			
153	(NGO Ship Breaking Platform, 2014a)	-	x	x	x	x	x		

154	(NGO Ship Breaking Platform, 2014a)	-	x	x	x	x	x		
155	(Sahu, 2014)	-	x	x	x				
156	(Taylan, 2014)	Ship recycling; Scrap metal; Hong-Kong Convention; Asbestos	x	x	x	x	x		
157	(Thanikachalam, 2014)	Recycling, Environmental, Hazardous, Safety, Convention	x		x	x			
158	(Wu et al., 2014)	Cancer incidence, Standardized incidence ratios (SIRs), Shipbreaking workers, Asbestos			x				
159	(Yujuico, 2014)	Ship recycling, Hong Kong Convention. California effect, Demandeur pays	x						

160	(Fakhruddin et al., 2015)	-				x				
161	(Frey, 2015)	Ship Breaking; Hazardous Wastes; Environmental Injustice; Risk Globalization; World-Systems Theory; Ecological Unequal Exchange; Political Ecology; Capital Accumulation; Recycling	x	x	x	x				
162	(Garmer et al., 2015)	Ship recycling, Ship breaking, Risk assessment, End-of-life vessels, Occupational risk			x					

163	(Hiremath et al., 2015)	Ship recycling, Ship dismantling, Hazardous waste, Emission factor, Hong-Kong convention, European Legislation				x			
164	(Hossain, 2015)	Ship recycling; Breaking; Dismantling; Socio-industrial safety; Environmental hazards		x	x	x			
165	(Kara et al., 2015)	Trace elements, Sediment and seawater, Principal component analysis, Sediment quality guidelines, Industrial region, Air pollution				x			

166	(Kurt et al., 2015)	risk, hazard, risk assessment, ship recycling, ship breaking, ship dismantling, job task analysis			x				
167	(Mizanur Rahman and Mayer, 2015)	Bangladesh, Metal, Ship recycling, Social embeddedness		x					
168	(NGO Ship Breaking Platform, 2015)	-	x	x	x	x	x		
169	(Nøst et al., 2015)	-				x			
170	(Sujauddin et al., 2015b)	Bangladesh Material flow analysis Ship breaking Lifespan		x			x		
171	(Wu et al., 2015)	-			x				

172	(Alcaidea et al., 2016)	Ship recycling methods, Reefing, Cost–benefit analysis, Environmental impact, Life cycle analysis	x						
173	(Choi et al., 2016)	-					x		
174	Fariya et al., 2016	-							x
175	Fariya et al., 2016	AHP, Green technologies, Ship breaking, Ship recyling, SWOT.			x	x	x		
176	(Haque, 2016)	Ship breaking, Pollution, Environmental impact, Occupational health, Safety, Management system, Bangladesh			x				
177	(Hossain et al., 2016)	-	x		x	x			

178	(ILPI, 2016)	End-of-life ships, Ship recycling, Material quantification, Ship scrap, Waste management, Design for recycling	x		x	x	x		
179	(Jain et al., 2016)	ship breaking, ship recycling, hazardous materials management, material flow analysis, Bangladesh						x	
180	(Koide et al., 2016)	ship dismantling, obsolete vessels, Ship Recycling, Beaching method, Energy Consumption					x		
181	(Mathesh and Babu, 2016)	-					x		
182	(Argüello Moncayo, 2016)	-	x						

183	(NGO Ship Breaking Platform, 2016)	-	x	x	x	x	x		
184	(Rahman et al., 2016)	Ship recycling, Steel production, Life cycle assessment, Rerolling mills. Resource use, Greenhouse gas emissions		x	x	x			
185	Rahman and Mayer (2016)	Administrative capacity , Compliance, Deposit refund system, Hong Kong Convention Policy gap analysis	x	x					
186	(Watagawa et al., 2016)	-						x	
187	(Ahammad and Sujauddin, 2017)	-	x	x		x			
188	(Alcaide et al., 2017)	Ship recycling, Shipbreaking, European Union,	x						

		Stakeholders' perceptions							
189	(Devault et al., 2017)	ship Recycling Facilities. Wrecks, Artificial reef, Ship recycling, Shipbreaking, Tourism, Diving, Working conditions	x	x		x			
191	Fariya et al., 2017	Risk, Ship Recycling, Madura, FMEA			x	x			

192	(Jain and Pruyn, 2017)	End-of-life ships, EU regulation, Hazardous waste, Hong Kong convention, Maritime economics, Material composition, Regulatory affairs, Scrap, Ship breaking, Ship recycling, Waste management	x	x					
193	(Jain et al., 2017)	Ship recycling, Ship breaking, Green ship recycling, Material flow analys						x	
194	(Jain, 2017)	-						x	

195	Kurt et al., 2017	Ship recycling, Ship dismantling, Noise exposure, Hearing loss, Occupational noise			x				
196	(Kutub et al., 2017)	Ship breaking activities, Environmental impact, Health impact, Pollution, Safety of workers, Coastal management		x	x	x			
197	(NGO Ship Breaking Platform, 2017)	-	x	x	x	x	x		
198	(Rahman, 2017)	Ship Recycling, Beach Method, Economic Contribution, Environmental Impact		x		x	x		

199	(Schøyen et al., 2017)	Ship-owner, Ship recycling, Ship scrapping, Environmental and safety conditions, Norway, Exploratory case study	x	x		x			
200	(Sujauddin et al., 2017)	Bangladesh, industrial ecology intensity of use, material flow analysis (MFA), ship breaking industry, steel recycling					x		
201	Gunbeyaz, et al., 2018	ship recycling discrete event simulation process optimisation					x		
202	Somarajan et al., 2018	strategic, guidance, india, ship recycling	x						

203	Du, et al., 2018	Ship recycling, Hazardous materials, Disposal methods, Practical measures				x				
204	Jain and Pruyn, 2018	Ship recycling, Ship breaking, Plasma gasification, Waste-to-energy, Waste management, Economic analysis		x		x	x			
205	Gunbeyaz, et al., 2019	ship recycling, training, gap analysis, curriculum development			x					
206	Ozturkoglu et al., 2019	Preventative model, Risk management, Fuzzy DEMATEL		x	x	x				
207	Ocampo et al., 2019	Ship recycling, Decommissioning, Shipyard, Sustainability, LDT, Scrapping		x		x				

208	Eronat et al., 2019	Oil pollution from ships, Ship recycling, The synthetic radar monitoring (SAR), Spatio-temporal analysis, Çandarlı Bay (Turkey)				x			
209	Devaux et al., 2019	Financial instruments, Pollution, Hong Kong convention, EU regulation on ship recycling,World trade organisation	x	x	x	x			
210	Gunbeyaz, et al., 2020	ship recycling, cutting techniques, plasma cutting					x		
211	Hsuan and Parisi, 2020	Ship recycling, Supply chain management, Regulation	x	x					
212	Singh et al., 2020	Asbestos exposure, Mesothelioma, Ship recycling			x				

213	Rahman et al., 2020	circular economy, disruption response, global circular economy, scenario analysis, ship recycling		x					
214	Benjamin and Figuereido, 2020	Ship recycling, Amazon, Brazil, Potential market		x					
215	Sunaryo et al., 2020	Hong Kong Convention, ship recycling yard, design, compliant							x
216	Zhou et al., 2021	Green ship recyclingOrganisation and managementHazardous materialsStructural equation modelling	x			x			
217	Zhou et al., 2021	Ship recycling, Dismantling operation management, Hazardous materials, Personal safety, Structural equation modelling			x	x			

218	Solakivi et al., 2021	Ship recycling, Ship dismantling, Ship-breaking capacity, Market potential, EU Ship recycling regulation, European list		x					
219	Sivaprasad and Nandakumar, 2021	ship recycling, expert system							x
220	Mathew, 2021	Ship recycling, externality, ship recycling nations	x	x					

Authors	Law, social and policy	Economic Impact	Health and safety	Environmental impact and waste management	Process analysis and best practice	Training	Process optimisation/ yard design
ShipDISMANTL, 2009	X	X			X		
SAFEREC, 2005	X		X	X	X	X	
DIVEST, 2008-2011	X	X	X	X	X	X	X
ShipDIGEST, 2013	X		X		X	X	

Boatcycle Project, 2012	X	X	X	X	X		
BOATDIGEST, 2013	X		X		X	X	
Shiprec, 2013	X	X	X	X	X		
IMO, 2017	X	X	X	X	X	X	
SSRI, 2019	X	X	X	X	X	X	
DCF, 2020	X		X	X	X		

APPENDIX 2: In-depth interview questions designed for each of the seven stakeholder groups

Ship Owners
• What factors influence your decision to decommission a ship for recycling? • What are your primary concerns when selecting a recycling facility? • How do economic considerations influence your decisions related to ship recycling? • How do you ensure compliance with regulations related to ship recycling?
Recycling Facility Managers
• Can you describe the main steps and processes in ship recycling at your facility? • What are the main challenges and difficulties you face in managing the recycling process? • How do you manage health and safety risks for workers in your facility? • What practices do you follow to minimise the environmental impact of ship recycling?
Workers
• Can you describe your daily tasks and responsibilities in the ship recycling process? • What health and safety concerns do you have in your work, and how are they addressed? • How does the recycling facility support you in carrying out your duties effectively and safely?
Regulatory Bodies
• What are the key regulations that govern the ship recycling process? • How do you monitor compliance with these regulations?

• What are the main challenges in regulating the ship recycling industry?
Community Representatives
• How does the ship recycling process impact your community? • What concerns does the community have regarding ship recycling activities? • Are there mechanisms for the community to express its concerns and influence decision-making related to ship recycling?
Logistics Service Providers
• What role do you play in the ship recycling process? • What challenges do you face in providing logistics services for ship recycling? • How do you coordinate with ship owners and recycling facilities?
Waste Management Companies
• How do you handle waste materials generated from ship recycling? • What regulations govern the disposal of ship recycling waste? • What challenges do you face in managing ship recycling waste, and how do you address them?

APPENDIX 3: Templates for Data Collection

Document 1: Data collection study

Name of Yard:					
Date:					
Data for Discrete Event Simulation					
No	Process	Detailed Job task	Number of resources	Specification	Total time
Data for Hazard Identification					
No	Process	Detailed Job Task	Hazard Involved		

Document 2: List of Detailed Job Task in Ship Recycling Process

No.	Job tasks
Pre-recycling	
1	**Pre-survey of the ship during on board before docking including** Surveyor travel to ship Surveyor access to ship Overall survey on board the ship Leaving the ship Transport back to land
2	**Preparation and check for transportation plan, ship recycling plan and IHM during on board before docking**
3	**Ship transport to Yard during on board before docking**
	other activities
Primary block breaking area	
4	**Docking procedures at dry dock**
5	**Conduct IHM survey at dry dock including;** (ASSUMING IHM IS CONDUCTED BY THE YARD PERSONNEL, NOT EXTERNALS) Access to the ship
6	**Conduct IHM survey at dry dock including;** Movement on-board the ship

	Taking samples on board the ship from Accommodation area, Engine room, Bridge, exposed deck, cargo holds or tanks and other spaces
7	**Disinfection for vermin and bugs at dry dock**
8	**Identification of complementary goods by port authority at dry dock** Port authority boards ship and inspects
9	**Remove fuel and sludge from ship and determination of amounts custom at dry dock including;** Access ship
10	**Remove fuel and sludge from ship and determination of amounts custom at dry dock including;** Set-up pumps Emptying the fuel tanks Storage & weighing the fuel and sludge
11	**Remove fuel and sludge from ship and determination of amounts custom at dry dock including;** Set-up pumps Emptying the fuel tanks Storage & weighing the fuel and sludge
12	**Removal of HAZMAT at dry dock including;** Access ship Movement on-board the ship

13	**Removal of HAZMAT at dry dock including;** Accessing the hazmat (removal of the panels/equipment/furniture etc.) Removal of hazardous materials Transfer of the hazardous material on-shore Storing the hazardous material
14	**Removal of HAZMAT at dry dock including;** Transfer of the hazardous material on-shore Storing the hazardous material
15	**Removal of HAZMAT at dry dock including;** Removal of hazardous materials Transfer of the hazardous material on-shore Storing the hazardous material
16	**Removal of HAZMAT at dry dock including;** Transfer of the hazardous material on-shore Storing the hazardous material
17	**Gas free and safety check including;** Access ship and survey
18	**Gas free and safety check including;** Gas free procedure for cargo & fuel oil tanks including their lines
19	**Gas free and safety check including;** Gas free procedure for cargo & fuel oil tanks including their lines

20	**Security & safety measures at dry dock including;** Placing oil booms Placing signs/marks around the ship
21	**Cut and install the access ways and ventilation to the ship at dry dock**
22	**Removal of navigational equipment at navigation bridge in dry dock including;** Transfer to shore Transfer to storage
23	**Removal of navigational equipment at navigation bridge in dry dock including;** Removal the navigational equipment using manual and powered tools
24	**Removal of navigational equipment at navigation bridge in dry dock including;** Removal the navigational equipment using manual and powered tools
25	**Removal of navigational equipment at navigation bridge in dry dock including;** Removal the navigational equipment using manual and powered tools
26	**Removal of furniture at navigation bridge in dry dock including;** Transfer to shore Transfer to storage
27	**Removal of furniture at navigation bridge in dry dock including;** Removal the furniture using manual and powered tools
28	**Removal of furniture at navigation bridge in dry dock including;** Removal the furniture using manual and powered tools

29	**Removal of furniture at navigation bridge in dry dock including;** Removal the furniture using manual and powered tools
30	**Removal of cables and electronic at dry dock including;** Transfer to shore Transfer to storage
31	**Removal of cables and electronic at dry dock including;** Removal the cables using manual and powered tools
32	**Removal of cables and electronic at dry dock including;** Transfer to shore Transfer to storage
33	**Removal of pipes at dry dock including;** Cutting the pipes and removal from the ship Transfer to shore Transfer to storage
34	**Segregation of material above at dry dock**
35	**Loading reusable material at dry dock including;** Lifting Loading
36	**Transport reusable material to storage at dry dock including;** Loading the forklift

	Transport in the yard Offloading
37	**Reusable material transfer from yard at dry dock including;** Loading to truck Transfer from yard
38	**Removal hull equipment such as winch, crane and cargo line at exposed deck in dry dock including;** Removal of the equipment (cutting or normal removal) Transfer to shore(storage)
39	**Cutting hull equipment into sections at exposed deck in dry dock** only if equipment is too old and beyond any use including; Cutting with torches Transfer the bits to shore
40	**Removal of interior and equipment at superstructure in dry dock including;** Removal of remaining equipment on board
41	**Removal of interior and equipment at superstructure in dry dock including;** Removal of remaining equipment on board Transfer to shore
42	**Cutting interior and equipment into sections with torch at superstructure in dry dock only if equipment is too old and beyond any use**

	Cutting Transfer to shore(storage)
43	**Removal of machineries such as engine, generator at machinery space in dry dock**
	other activities
Secondary block breaking area	
44	**Cutting machinery into section at secondary cutting zone**
45	**Discharge of remaining liquid waste on bilge well and engine room bottom and cleaning at machinery space in dry dock including;** Setting Pumps Transferring the liquid out
46	**Cutting hull structure into section at dry dock(primary cutting zone) including;** Cutting with torches
47	**Cutting blocks into smaller pieces at secondary cutting zone including;** Cutting blocks to small pieces (1x1) with torches
48	**Segregation (plate and HAZMAT) at secondary cutting zone**
49	**Loading steel to transport at secondary cutting zone**
	other activities
Storages area	
50	**Transport out from the yard at storage zone**
51	**Loading HAZMAT to transport at storage zone**

52	**Transport out from the yard at storage zone and outside of yard**
53	**Stockpiling of assorted, finished materials**
	other activities
Waste disposal facilities	
54	**Land filling**
55	**Incineration**
56	**Wastewater treatment**
	other activities

Document 3: List of Hazard and its causal risk factor

No. Hazards	Potential Hazards	Causal Risk Factors	
		No	**Caused by**
1	General travel hazards	1.1	Usual on-board hazards/slip/trip/falls from height/impact with object etc
2	Office hazards	2.1 2.2 2.3	Wrong planning Communication errors Wrong decision
3	Ship accidents such as collision, grounding	3.1 3.2 3.3 3.4 3.5 3.6	*Loss of propulsion or control (in case of self-propulsion) *Heavy weather *Failure of the towing (in case of towing) *Failure of towing wire or equipment (in case of towing) *Improper towing arrangement or plan (in case of towing) *Wrong draft or calculation of weight and centre of gravity
4	Failure of docking	4.1 4.2 4.3 4.4 4.5	*Improper docking plan *Failure of positioning *Failure of control of wire, winches and other equipment's *Wrong lay out of supporters *Failure of plugging
5	Exposure that can give effects in a long	5.1 5.2	*Improper wearing of PPE *Asbestos fibres

	term: Hazardous substances	5.3	*PCBs and PVC and CFC’s
	and wastes	5.4	*Heavy and toxic metals (lead, mercury, cadmium, copper, zinc, etc)
	-Asbestos - in hanger liners,	5.5	*Dusts
	mastic under	5.6	*Paints and coatings
	isolation, cloth under isolation,	5.7	*Combustible Materials
	cable, lagging	5.8	*Foam Insulation
	and insulation on pipes and	5.9	*Organic substances (TBT, isocyanates etc. in marine paint)
	hull, adhesive,	5.10	*Volatile organic compounds (solvents)
	gaskets on piping connections,	5.11	*Hydrogen sulfide H2S (has a distinctive smell-like rotten eggs)
	and valve	5.12	*Carbone monoxide (CO) has no smell, measured by testing)
	packing.	5.13	*Batteries
	-Polychlorinated biphenyls	5.14	*Fire-fighting liquids
	(PCBs) – in	5.15	*Compressed gas under pressure
	rubber products such as hoses,	5.16	*Exposure to hazardous liquids or gases or material substances
	plastic foam	5.17	*Redundant gases
	insulation, cables, silver paint,	5.18	*Oil and fuel
	habitability paint,	5.19	*Cleaning compounds
	felt under septum plates, plates	5.20	*CO2
	on top of the	5.21	*Bilge and ballast water
	hull bottom and primary paint	5.22	*Radiation sources
	on hull steel.	5.23	*Timber

	-Hazardous materials and chemicals – including heavy metals in ship transducers, ballast, and paint coatings; mercury in fluorescent light tubes, thermometers, electrical switches, light fittings, fire detectors and tank level indicators; and chlorofluorocarbons (CFCs) in self-contained refrigeration devices such as water coolers and freezer units.	5.24 5.25 5.26 5.27	*Corroding *Other chemicals *Evaporated rests in tank or mud bed or leaking packing or valves *Hydrogen sulphide at microbiological activity or breaking down
6	Suffocating or drowning due to the confined space access & works	6.1 6.2 6.3	*Lack of control of Oxygen deficiency in confined spaces (should be 20-22 volume percentage (less than 19,5 is dangerous and one should not enter without PPE, if higher than 22% there can be an explosive mixture)) *Lack of proper ventilation *Lack of proper training when entering a confined space etc

		6.4 6.5 6.6 6.7 6.8 6.9 6.10	*Drowning for floating or partially floating structures *Gases and fumes heavier than air which presses the oxygen away *Oxidation processes that consume oxygen (e.g. open flame or welding) *Closed entry to space *Lack of rescue team standing standby and no attendant (with correct PPE) being in constant contact with workers inside a confined space) *Lack of notice or colour sign indicating that work is going on in the confined space
7	Impact with a falling object	7.1 7.2 7.3	*Improper loading and securing *Snapping of cables, ropes, chains, slings *Wire and rope breakage, wear and corrosion of wire ropes
8	Hazardous handling, overloading of part of the body	8.1 8.2 8.3 8.4 8.5	*Handling heavy objects *Repetitive strain injuries *Awkward postures *Repetitive work and monotonous work *Excessive workload
9	transportation and material handling hazard	9.1 9.2 9.3	*Trucks *Transport vehicles *Cranes

10	Fire, explosion from ignited insulation, matting, lagging, and residual fuel; and lubricants and other flammable liquids.		*Uncoated tools when there is a risk for sparks *Explosive materials *Explosive gases *Flammable materials *Chemical reactions *Inadequate fire protection measures *Lack of appropriate emergency response, rescue and first-aid personnel services *Lack of explosion proof light or/and equipment *Unprotected disposal/storage place of e.g. fuel, oil, grease
11	Penetration of sharp objects		*Sharp objects *Sharp-edged tools
12	Electric shock		*Connection to batteries *Wrong connection to electric power source from onshore
13	Impact with a falling object		*Improper loading and securing *Snapping of cables, ropes, chains, slings *Wire and rope breakage, wear and corrosion of wire ropes
14	Impact with a flying object		Being crushed by flying object
15	Falling on the same level-stumbling, slipping etc.		Slipping on wet surfaces or on something laying or fastening on the walking surface

16	Falling to a lower level		*Falls from height inside ship structures or on the ground *Access in progressively dismantled vessels (floor, stairs, passageways) *Collapse of structure *Scaffolding, platforms, fixed and portable ladders
17	Squeezing or crushing		Stuck by moving objects Caught in or compressed Shackles, hooks, chains Cranes, winches, hosting and hauling equipment
18	Electrical energy available		*Electricity /electrocution *Electrostatic recharging (could happen when using powerful jet of water
20	Poisoning		
21	Suffocating or drowning		Lack of control of Oxygen deficiency in confined spaces (should be 20-22 volume percentage (less than 19,5 is dangerous and one should not enter without PPE, if higher than 22% there can be an explosive mixture))
			Lack of proper ventilation
			Lack of proper training when entering a confined space etc
			Drowning for floating or partially floating structures
			Gases and fumes heavier than air which presses the oxygen away
			Oxidation processes that consume oxygen (e.g. open flame or welding)
			Closed entry to space

			Lack of rescue team standing standby and no attendant (with correct PPE) being in constant contact with workers inside a confined space)
			Lack of notice or colour sign indicating that work is going on in the confined space
22	Hazardous persons or animals		Toxic marine organisms
			Animal bites
			Risk of communicable diseases transmitted by pets, vermin, rodents, insects and other animals that may infest the ship
			Vectors of infectious diseases (TB, malaria, dengue fever, hepatitis, respiratory infections etc
23	Exposure that can give effects in a long term: Hazardous Physical situation		Poor illumination
			Excess noise – associated with grinding, hammering, metal cutting, and other activities
			Vibrations
			Extreme temperatures
			Radiation (UV, radioactive materials)
24	Hazardous psychosocial situations		Mental stress
			Human relations (aggressive behaviour, alcohol and drugs abuse, violence)
			Long working hours
			Shift work
			Night work

			Temporary employment
			Poverty
			Low wages
			Minimum age
			Lack of education and social environment
			Poor work organisation;
25	Hazardous standard of workplace		Lack of PPE (helmet, safety shoes (oil resistant), safety goggles, gloves, ear plugs/ ear muffs, dust mask or/and gas mask (fresh air), safety belt and life line, apron, face shield with colour glass, fire extinguisher near cutting, fire guard, when cutting: leather used as material PPE
			Lack of special routines and PPE when collect and dispose fuel oil, grease and other combustible products, asbestos etc
			Inadequate maintenance of PPE
			Housekeeping practices
			Safety signs
			Lack of health and safety training to carry out the work in a safe manner
			Inadequate accident prevention and inspection
			Inadequate emergency
			Lack of regular exercises in emergency prevention, preparedness and response procedures
			Escape routes not free for possible evacuation

			First-aid and rescue facilities
			Inadequate housing and sanitation
			Lack of medical facilities and social protection
			Lack of hazard communication (storage, labelling, material safety data sheets
			Lack of standard work area and procedures. (There cannot be a work system, which is standard but unsafe. Standard way of doing a work is definitely the safest way too. Occupational safety ensures higher productivity).

Document 4: Hazard Identification through expert Judgement

Name of process																										
No	Detail Job Task (Refer to Document 2)	Hazard No. (Assess OK or Not OK for different job task, refer to Document 3)																								
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1																										
2																										
3																										

Document 5: Hazard Identification through expert Judgement

No	Process	Detailed job task	Causal risk factor	Risk Level		
				Severity	Consequence	Detection
1						
2						
3						

Note

Severity	Occurrence	Detection	Score
Death	Very frequent once day	No chance	5
Disability	Once week, frequent	Remote chance	4
Longer reporting sick >14d	Quite frequent once month	Low chance	3
Shorter reporting sick <14d	Quite unusual	Moderate chance	2

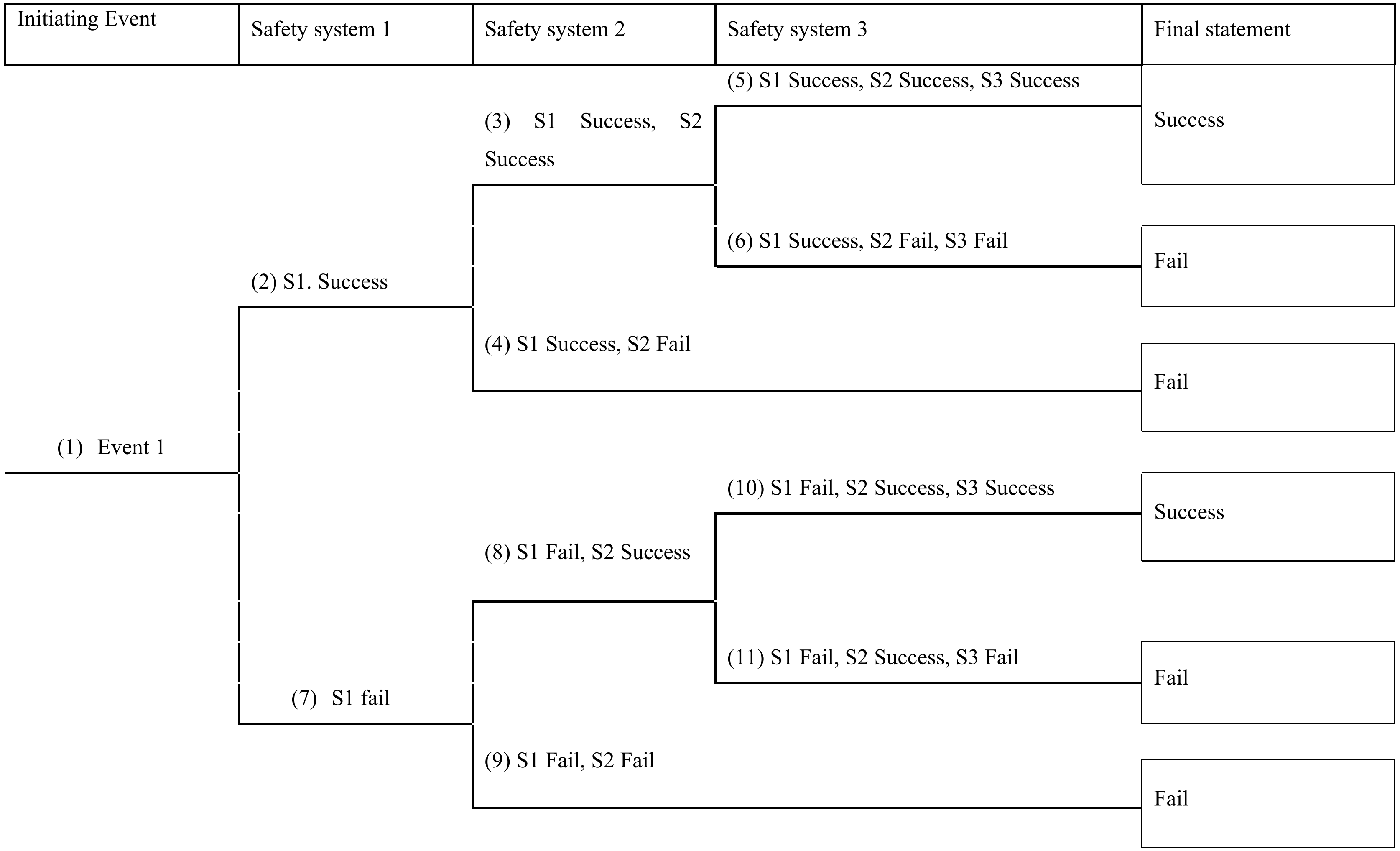
Injury with no sick reporting	Unlikely	High chance	1
Negligible injury	Very unlikely	Very high chance	0

Document 6: Frequency and Consequence Analysis

Step 1: Data for Event Tree Analysis

No	Initial Event	Safety system 1	Safety system 2	Safety system 3	etc

Step 2: Construct Event Tree Diagram (example)



Step 3: Questionnaire for the expert

Event No.	Failure Possibilities	Consequence
(2) S1. Success		
(3) S1 Success, S2 Success		
(5) S1 Success, S2 Success, S3 Success		
(8) S1 Fail, S2 Success		
(10) S1 Fail, S2 Success, S3 Success		

Table 1. A set of linguistic failure possibilities and its possibilities value in a year

Failure possibilities (H)	**Score**	**Value in crisp number (n)**
H1= Very frequent, once a day	5	365
H2= Frequent, once per week	4	52
H3= Quite frequent, once per month	3	12
H4= Quite unusual, once a year	2	1
H5= Unlikely, once per 10 years	1	0.1
H6=Very unlikely, once per 100 years		00.1 c
Degree of severity	Score	Crisp
Very low	1	0.125

Low	2	0.25
Reasonably low	3	0.375
Moderate	4	0.5
Reasonably High	5	0.625
High	6	0.7
Very High	7	0.875

APPENDIX 4: Estimation of performance data

The following table, the thicknes come from…

The penetration, preheat, reposition… are predicted by data collection study.. manufacturer etc..

Number of block	Part	Bottom Hull line (metre)	Thickness	penetration			Total penetration time	Preheat time	Reposition time (minute)	Time 2 (minutes)
				number	time	thickness				
7	Cutting Derrick	0.00	0.00	0	0.0	0	0.00	0.00	0.00	0.00
10	Cutting Upper Hull 2 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
11	Cutting Upper Hull 2 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
12	Cutting Upper Hull 3 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
13	Cutting Upper Hull 3 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
14	Cutting Upper Hull 4 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
15	Cutting Upper Hull 4 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
16	Cutting Upper Hull 5 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
17	Cutting Upper Hull 5 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
19	Cutting bottom hull 1 portside	6.90	0	9	0.2	8	2.57	0.50	1.00	13.19
20	Cutting bottom hull 2 starboard	6.90	0	9	0.2	8	2.57	0.50	1.00	13.19
21	Cutting bottom hull 2 portside	6.90	0	9	0.2	8	2.57	0.50	1.00	13.19
22	Cutting double bottom 1 starboard	4.00	0	9	0.2	8	2.57	0.50	1.00	8.73
23	Cutting double bottom 1 portside	0.00	0.00	0	0.0	0	0.00	0.00	0	0.00
24	Cutting navigation deck	16	10	0	0.0	0	0.00	0.00	0	24.62
26	Cutting double bottom 2 starboard	0	0	0	0.0	0	0.00	0.00	0	0.00
29	Cutting double bottom 3 starboard	0	0	0	0.0	0	0.00	0.00	1.00	0.00
30	Cutting double bottom 3 portside	0	0	0	0.0	0	0.00	0.00	1.00	0.00
31	Cutting bridge deck	15	10	0	0.0	0	0.00	0.00	1.00	23.08

32	Cutting bottom hull 4 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
33	Cutting bottom hull 4 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
34	Cutting bottom hull 5 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
35	Cutting bottom hull 5 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
38	Cutting 41 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
39	Cutting 42 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
40	Cutting 43 starboard	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
41	Cutting 44 portside	6.90	10	9	0.2	8	2.57	0.50	1.00	13.19
42	Cutting upper machinery space starboard	6.90	10	7	0.2	8	2.00	0.50	1.00	12.62
43	Cutting upper machinery space portside	6.5	10	7	0.2	8	2.00	0.50	1.00	12.00
44	Cutting upper steering gear	1.79	10	6	0.2	8	1.71	0.50	1.00	4.47
45	Cutting bottom machinery space starboard	6.5	10	7	0.2	8	2.00	0.50	1.00	12.00
46	Cutting bottom machinery space portside	6.5	10	7	0.2	8	2.00	0.50	1.00	12.00
47	Cutting bottom steering gear	3.58	10	2	0.2	8	0.57	0.50	1.00	6.08
48	Cutting double bottom 6 starboard	0	0	0	0.0	0	0.00	0	0	0.00
49	Cutting double bottom 6 portside	0	0	0	0	0	0	0	0	0
50	Cutting double bottom 7 starboard	0	0	0	0	0	0	0	0	0

Number of block	Part	Bottom transverse	thickness	penetration			Total penetration time	Preheat time	Reposition time (minute)	Time 3 (minutes)
				number	time	thickness				
7	Cutting Derrick	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	Cutting Upper Hull 2 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

11	Cutting Upper Hull 2 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	Cutting Upper Hull 3 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	Cutting Upper Hull 3 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	Cutting Upper Hull 4 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	Cutting Upper Hull 4 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	Cutting Upper Hull 5 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	Cutting Upper Hull 5 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	Cutting bottom hull 1 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	Cutting bottom hull 2 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	Cutting bottom hull 2 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	Cutting double bottom 1 starboard	4.00	12	0.00	0.00	0.00	0.00	0.50	1.00	6.67
23	Cutting double bottom 1 portside	4.00	12.00	0.00	0.00	0.00	0.00	0.50	1.00	6.67
24	Cutting navigation deck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26	Cutting double bottom 2 starboard	4.00	12.00	0.00	0.00	0.00	0.00	0.50	1.00	6.67
29	Cutting double bottom 3 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30	Cutting double bottom 3 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
31	Cutting bridge deck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	Cutting bottom hull 4 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33	Cutting bottom hull 4 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	Cutting bottom hull 5 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35	Cutting bottom hull 5 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
38	Cutting 41 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	Cutting 42 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40	Cutting 43 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
41	Cutting 44 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
42	Cutting upper machinery space starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43	Cutting upper machinery space portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
44	Cutting upper steering gear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

45	Cutting bottom machinery space starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
46	Cutting bottom machinery space portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47	Cutting bottom steering gear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
48	Cutting double bottom 6 starboard	4.00	12.00	9	1	8	12.86	0.50	1.00	20.00
49	Cutting double bottom 6 portside	4.00	12.00	9	1	8	12.86	0.50	1.00	20.00
50	Cutting double bottom 7 starboard	4.00	12.00	9	1	8	12.86	0.50	1.00	20.00

Number of blocks	Part	Longitudinal bottom	thickness	penetration			Total penetration time	Preheat time	Reposition time (minute)	Time 4 (minutes)
				number	time	thickness				
7	Cutting Derrick	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	Cutting Upper Hull 2 starboard	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	Cutting Upper Hull 2 portside	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	Cutting Upper Hull 3 starboard	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	Cutting Upper Hull 3 portside	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	Cutting Upper Hull 4 starboard	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	Cutting Upper Hull 4 portside	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
16	Cutting Upper Hull 5 starboard	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	Cutting Upper Hull 5 portside	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	Cutting bottom hull 1 portside	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	Cutting bottom hull 2 starboard	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	Cutting bottom hull 2 portside	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22	Cutting double bottom 1 starboard	6.90	12	9	1	1	12.86	0.50	1.00	13.17
23	Cutting double bottom 1 portside	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	Cutting navigation deck	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00

26	Cutting double bottom 2 starboard	6.90	12	9	8.00	0.20	102.86	0.5	1.00	14.17
29	Cutting double bottom 3 starboard	0.00	0	0	0	0	0.00	0.00	0.00	0.00
30	Cutting double bottom 3 portside	6.90	12	9	8	0.20	102.86	0.5	1.00	14.17
31	Cutting bridge deck	0.00	0	0	0	0	0.00	0.00	0.00	0.00
32	Cutting bottom hull 4 starboard	0.00	0	0	0	0	0.00	0.00	0.00	0.00
33	Cutting bottom hull 4 portside	0.00	0	0	0	0	0.00	0.00	0.00	0.00
34	Cutting bottom hull 5 starboard	0.00	0	0	0	0	0.00	0.00	0.00	0.00
35	Cutting bottom hull 5 portside	0.00	0	0	0	0	0.00	0.00	0.00	0.00
38	Cutting 41 starboard	0.00	0	0	0	0	0.00	0.00	0.00	0.00
39	Cutting 42 portside	0.00	0	0	0	0	0.00	0.00	0.00	0.00
40	Cutting 43 starboard	0.00	0	0	0	0	0.00	0.00	0.00	0.00
41	Cutting 44 portside	0.00	0	0	0	0	0.00	0.00	0.00	0.00
42	Cutting upper machinery space starboard	0.00	0	0	0	0	0.00	0.00	0.00	0.00
43	Cutting upper machinery space portside	0.00	0	0	0	0	0.00	0.00	0.00	0.00
44	Cutting upper steering gear	0.00	0	0	0	0	0.00	0.00	0.00	0.00
45	Cutting bottom machinery space starboard	0.00	0	0	0	0	0.00	0.00	0.00	0.00
46	Cutting bottom machinery space portside	0.00	0	0	0	0	0.00	0.00	0.00	0.00
47	Cutting bottom steering gear	0.00	0	0	0	0	0.00	0.00	0.00	0.00
48	Cutting double bottom 6 starboard	6.90	12	9	8	0.20	102.86	0.5	1.00	14.17
49	Cutting double bottom 6 portside	6.90	12	9	8	0.20	102.86	0.5	1.00	14.17
50	Cutting double bottom 7 starboard	6.90	12	9	8	0.20	102.86	0.5	1.00	14.17

APPENDIX CHAPTER 10: Time recorded for cutting time

Number of block	Part	Total Time (Minutes)
7	Cutting Derrick	2.72
10	Cutting Upper Hull 2 starboard	19.53
11	Cutting Upper Hull 2 portside	19.53
12	Cutting Upper Hull 3 starboard	19.39
13	Cutting Upper Hull 3 portside	19.39
14	Cutting Upper Hull 4 starboard	19.53
15	Cutting Upper Hull 4 portside	19.53
16	Cutting Upper Hull 5 starboard	19.70
17	Cutting Upper Hull 5 portside	19.70
19	Cutting bottom hull 1 portside	17.23
20	Cutting bottom hull 2 starboard	17.23
21	Cutting bottom hull 2 portside	17.23

22	Cutting double bottom 1 starboard	21.97
23	Cutting double bottom 1 portside	12.24
24	Cutting navigation deck	26.12
26	Cutting double bottom 2 starboard	12.55
29	Cutting double bottom 3 starboard	5.58
30	Cutting double bottom 3 portside	5.58
31	Cutting bridge deck	25.58
32	Cutting bottom hull 4 starboard	17.23
33	Cutting bottom hull 4 portside	17.23
34	Cutting bottom hull 5 starboard	17.23
35	Cutting bottom hull 5 portside	17.23
38	Cutting 41 starboard	17.23
39	Cutting 42 portside	17.23
40	Cutting 43 starboard	17.23
41	Cutting 44 portside	17.23
42	Cutting upper machinery space starboard	17.01
43	Cutting upper machinery space portside	16.39
44	Cutting upper steering gear	6.97

45	Cutting bottom machinery space starboard	18.35
46	Cutting bottom machinery space portside	18.35
47	Cutting bottom steering gear	13.66
48	Cutting double bottom 6 starboard	24.04
49	Cutting double bottom 6 portside	24.04
50	Cutting double bottom 7 starboard	24.04

Estimation for secondary cutting time

Number	Part	Side hull line 1 (meter)	Smaller plate length		total line cutting (meter)	Thicknes	penetration			total penetration	total preheat	total reposition	Total Time 1 (minutes)
							number	thickness	time				
1	Primary Cutting Collision Bulkhead	4.46	1.50	3	13.26	10.00	0.00	0.00	0.00	0.00	1.49	1.5	23.37
2	Primary Cutting fore peak	4.46	1.50	3	13.26	10.00	0.00	0.00	0.00	0.00	1.49	1.5	23.37
3	Cutting fore master	0.79	1.50	1	0.41	10.00	0.00	0.00	0.00	0.00	0.26	0.3	1.16
4	Cutting anchor station	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
5	Cutting Forecastle deck	1.20	1.50	1	0.96	10.00	0.00	0.00	0.00	0.00	0.40	0.4	2.28
6	Cutting Hatch Coming	0.79	1.50	1	0.41	0.00	0.00	0.00	0.00	0.00	0.26	0.3	1.16
8	Cutting Upper Hull 1 starboard	2.68	1.50	2	4.79	10.00	0.00	0.00	0.00	0.00	0.89	0.9	9.15
9	Cutting Upper Hull 1 portside	2.68	1.50	2	4.79	10.00	0.00	0.00	0.00	0.00	0.89	0.9	9.15
10	Cutting Upper Hull 2 starboard	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
11	Cutting Upper Hull 2 portside	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
12	Cutting Upper Hull 3 starboard	2.41	1.50	2	3.87	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.56

13	Cutting Upper Hull 3 portside	2.41	1.50	2	3.87	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.56
14	Cutting Upper Hull 4 starboard	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
15	Cutting Upper Hull 4 portside	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
16	Cutting Upper Hull 5 starboard	2.61	1.50	2	4.54	10.00	0.00	0.00	0.00	0.00	0.87	0.9	8.73
17	Cutting Upper Hull 5 portside	2.61	1.50	2	4.54	10.00	0.00	0.00	0.00	0.00	0.87	0.9	8.73
18	Cutting bottom hull 1 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
19	Cutting bottom hull 1 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
20	Cutting bottom hull 2 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
21	Cutting bottom hull 2 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
22	Cutting double bottom 1 starboard	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
23	Cutting double bottom 1 portside	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
24	Cutting navigation deck	2.40	1.50	2	3.84	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.51
25	Cutting double bottom 2 portside	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
26	Cutting double bottom 2 starboard	2.20	1.50	1	3.23	10.00	0.00	0.00	0.00	0.00	0.73	0.7	6.43
27	Cutting bottom hull 3 starboard	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
28	Cutting bottom hull 3 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
29	Cutting double bottom 3 starboard	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
30	Cutting double bottom 3 portside	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
31	Cutting bridge deck	2.40	1.50	2	3.84	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.51
32	Cutting bottom hull 4 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
33	Cutting bottom hull 4 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
34	Cutting bottom hull 5 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
35	Cutting bottom hull 5 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
36	Cutting boat deck	0.00	1.50	0	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00

37	Cutting machinery bulkhead	4.50	1.50	3	13.50	10.00	0.00	0.00	0.00	0.00	1.50	1.5	23.77
38	Cutting 41 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
39	Cutting 42 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
40	Cutting 43 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
41	Cutting 44 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
42	Cutting upper machinery space starboard	1.23	1.50	1	1.01	10.00	0.00	0.00	0.00	0.00	0.41	0.4	2.37
43	Cutting upper machinery space portside	1.23	1.50	1	1.01	10.00	0.00	0.00	0.00	0.00	0.41	0.4	2.37
44	Cutting upper steering gear	3.00	1.50	2	6.00	10.00	0.00	0.00	0.00	0.00	1.00	1.0	11.23
45	Cutting bottom machinery space starboard	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
46	Cutting bottom machinery space portside	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
47	Cutting bottom steering gear	3.30	1.50	2	7.26	10.00	0.00	0.00	0.00	0.00	1.10	1.1	13.37
48	Cutting double bottom 6 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
49	Cutting double bottom 6 portside	1.00	1.50	1	0.67	10	0	0	0	0	0.33	0.3	1.54
50	Cutting double bottom 7 starboard	1.00	1.50	1	0.67	10	0	0	0	0	0.33	0.3	1.54
51	Cutting double bottom 7 portside	1.00	1.50	1	0.67	10	0	0	0	0	0.33	0.3	1.54
52	Cutting after peak tank into 2 part	0.00	0.00	0	0.00	0	0	0	0	0	0.00	0.0	0.00

Number	Part	Side hull line 2 (meter)	Smaller plate length		total line cutting (meter)	Thicknes	penetration			total penetration	total preheat	total reposition	Total Time 1 (minutes)
							number	thickness	time				
1	Primary Cutting Collision Bulkhead	4.46	1.50	3	13.26	10.00	0.00	0.00	0.00	0.00	1.49	1.5	23.37
2	Primary Cutting fore peak	4.46	1.50	3	13.26	10.00	0.00	0.00	0.00	0.00	1.49	1.5	23.37
3	Cutting fore master	0.79	1.50	1	0.41	10.00	0.00	0.00	0.00	0.00	0.26	0.3	1.16
4	Cutting anchor station	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
5	Cutting Forecastle deck	1.20	1.50	1	0.96	10.00	0.00	0.00	0.00	0.00	0.40	0.4	2.28
6	Cutting Hatch Coming	0.79	1.50	1	0.41	0.00	0.00	0.00	0.00	0.00	0.26	0.3	1.16
8	Cutting Upper Hull 1 starboard	2.68	1.50	2	4.79	10.00	0.00	0.00	0.00	0.00	0.89	0.9	9.15
9	Cutting Upper Hull 1 portside	2.68	1.50	2	4.79	10.00	0.00	0.00	0.00	0.00	0.89	0.9	9.15
10	Cutting Upper Hull 2 starboard	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
11	Cutting Upper Hull 2 portside	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
12	Cutting Upper Hull 3 starboard	2.41	1.50	2	3.87	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.56
13	Cutting Upper Hull 3 portside	2.41	1.50	2	3.87	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.56
14	Cutting Upper Hull 4 starboard	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
15	Cutting Upper Hull 4 portside	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
16	Cutting Upper Hull 5 starboard	2.61	1.50	2	4.54	10.00	0.00	0.00	0.00	0.00	0.87	0.9	8.73
17	Cutting Upper Hull 5 portside	2.61	1.50	2	4.54	10.00	0.00	0.00	0.00	0.00	0.87	0.9	8.73
18	Cutting bottom hull 1 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
19	Cutting bottom hull 1 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
20	Cutting bottom hull 2 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
21	Cutting bottom hull 2 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
22	Cutting double bottom 1 starboard	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
23	Cutting double bottom 1 portside	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
24	Cutting navigation deck	2.40	1.50	2	3.84	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.51

25	Cutting double bottom 2 portside	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
26	Cutting double bottom 2 starboard	2.20	1.50	1	3.23	10.00	0.00	0.00	0.00	0.00	0.73	0.7	6.43
27	Cutting bottom hull 3 starboard	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
28	Cutting bottom hull 3 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
29	Cutting double bottom 3 starboard	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
30	Cutting double bottom 3 portside	2.00	1.50	1	2.67	10.00	0.00	0.00	0.00	0.00	0.67	0.7	5.44
31	Cutting bridge deck	2.40	1.50	2	3.84	10.00	0.00	0.00	0.00	0.00	0.80	0.8	7.51
32	Cutting bottom hull 4 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
33	Cutting bottom hull 4 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
34	Cutting bottom hull 5 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
35	Cutting bottom hull 5 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
36	Cutting boat deck	0.00	1.50	0	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00
37	Cutting machinery bulkhead	4.50	1.50	3	13.50	10.00	0.00	0.00	0.00	0.00	1.50	1.5	23.77
38	Cutting 41 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
39	Cutting 42 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
40	Cutting 43 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
41	Cutting 44 portside	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
42	Cutting upper machinery space starboard	1.23	1.50	1	1.01	10.00	0.00	0.00	0.00	0.00	0.41	0.4	2.37
43	Cutting upper machinery space portside	1.23	1.50	1	1.01	10.00	0.00	0.00	0.00	0.00	0.41	0.4	2.37
44	Cutting upper steering gear	3.00	1.50	2	6.00	10.00	0.00	0.00	0.00	0.00	1.00	1.0	11.23
45	Cutting bottom machinery space starboard	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
46	Cutting bottom machinery space portside	2.50	1.50	2	4.17	10.00	0.00	0.00	0.00	0.00	0.83	0.8	8.08
47	Cutting bottom steering gear	3.30	1.50	2	7.26	10.00	0.00	0.00	0.00	0.00	1.10	1.1	13.37

48	Cutting double bottom 6 starboard	1.00	1.50	1	0.67	10.00	0.00	0.00	0.00	0.00	0.33	0.3	1.69
49	Cutting double bottom 6 portside	1.00	1.50	1	0.67	10	0	0	0	0	0.33	0.3	1.54
50	Cutting double bottom 7 starboard	1.00	1.50	1	0.67	10	0	0	0	0	0.33	0.3	1.54
51	Cutting double bottom 7 portside	1.00	1.50	1	0.67	10	0	0	0	0	0.33	0.3	1.54
52	Cutting after peak tank into 2 part	0.00	0.00	0	0.00	0	0	0	0	0	0.00	0.0	0.00

Number	Part	bottom hull line (meter)	Smaller plate length		total line cutting (meter)	Thicknes	penetration			total penetration	total preheat	total reposition	Total Time 2 (minutes)
							number	thickness	time				
1	Primary Cutting Collision Bulkhead	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	Primary Cutting fore peak	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	Cutting fore master	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Cutting anchor station	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	Cutting Forecastle deck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Cutting Hatch Coming	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	Cutting Upper Hull 1 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
9	Cutting Upper Hull 1 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
10	Cutting Upper Hull 2 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
11	Cutting Upper Hull 2 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
12	Cutting Upper Hull 3 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38

13	Cutting Upper Hull 3 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
14	Cutting Upper Hull 4 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
15	Cutting Upper Hull 4 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
16	Cutting Upper Hull 5 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
17	Cutting Upper Hull 5 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
18	Cutting bottom hull 1 starboard	6.90	0.50	14	95.22	0	9	0.2	8	35.49	4.5	6.90	193.38
19	Cutting bottom hull 1 portside	6.90	0.50	14	95.22	0	9	0.2	8	35.49	4.5	6.90	193.38
20	Cutting bottom hull 2 starboard	6.90	0.50	14	95.22	0	9	0.2	8	35.49	4.5	6.90	193.38
21	Cutting bottom hull 2 portside	6.90	0.50	14	95.22	0	9	0.2	8	35.49	4.5	6.90	193.38
22	Cutting double bottom 1 starboard	4.00	0.50	8	32.00	10	9	0.2	8	20.57	4.5	4.00	78.30
23	Cutting double bottom 1 portside	4.00	0.50	8	32.00	10	9	0.2	8	20.57	4.5	4.00	78.30
24	Cutting navigation deck	16.00	0.50	32	512.00	10	0	0	0	0.00	0	16.00	803.69
25	Cutting double bottom 2 portside	0.00	0.50	0	0.00	0	0	0	0	0.00	0	0.00	0.00
26	Cutting double bottom 2 starboard	0.00	0.50	0	0.00	0	0	0	0	0.00	0	0.00	0.00
27	Cutting bottom hull 3 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
28	Cutting bottom hull 3 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38

29	Cutting double bottom 3 starboard	0.00	0.50	0	0.00	0	0	0	0	0.00	0	0.00	0.00
30	Cutting double bottom 3 portside	0.00	0.50	0	0.00	0	0	0	0	0.00	0	0.00	0.00
31	Cutting bridge deck	16.00	0.50	32	512.00	10	0	0	0	0.00	0	16.00	803.69
32	Cutting bottom hull 4 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
33	Cutting bottom hull 4 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
34	Cutting bottom hull 5 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
35	Cutting bottom hull 5 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
36	Cutting boat deck	25.60	0.50	51	1,310.72	10	0	0	0	0.00	0	25.60	2,042.09
37	Cutting machinery bulkhead	7.00	0.50	14	98.00	0	0	0	0	0.00	0	7.00	157.77
38	Cutting 41 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
39	Cutting 42 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
40	Cutting 43 starboard	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
41	Cutting 44 portside	6.90	0.50	14	95.22	10	9	0.2	8	35.49	4.5	6.90	193.38
42	Cutting upper machinery space starboard	6.90	0.50	14	95.22	10	7	0.2	8	27.60	3.5	6.90	184.49
43	Cutting upper machinery space portside	6.90	0.50	14	95.22	11	7	0.2	8	27.60	3.5	6.90	184.49
44	Cutting upper steering gear	1.79	0.50	4	6.41	10	6	0.2	8	6.14	3	1.79	20.79
45	Cutting bottom machinery space starboard	6.50	0.50	13	84.50	10	7	0.2	8	26.00	3.5	6.50	166.00

46	Cutting bottom machinery space portside	6.50	0.50	13	84.50	10	7	0.2	8	26.00	3.5	6.50	166.00
47	Cutting bottom steering gear	3.58	0.50	7	25.63	10	2	0.2	8	4.09	1	3.58	48.11
48	Cutting double bottom 6 starboard	6.9	0.50	14	95.22	0	0	0	0	0.00	0	6.90	153.39
49	Cutting double bottom 6 portside	6.9	0.50	14	95.22	0	0	0	0	0.00	0	0	146.49
50	Cutting double bottom 7 starboard	6.9	0.50	14	95.22	0	0	0	0	0.00	0	0	146.49
51	Cutting double bottom 7 portside	6.9	0.50	14	95.22	0	0	0	0	0.00	0	0	146.49
52	Cutting after peak tank into 2 part	6.9	0.50	14	95.22	0	0	0	0	0.00	0	0	146.49

Number	Part	Bottom Transverse (meter)	smaller plate length		total line cutting (meter)	thickness	penetration			total penetration	total preheat	total reposition	Total Time 3 (minutes)
							number	thickness	time				
1	Primary Cutting Collision Bulkhead	1.85	0.50	4	6.82	12.00	0.00	0.00	0.00	0.00	0	2	7.53
2	Primary Cutting fore peak	1.85	0.50	4	6.82	12.00	0.00	0.00	0.00	0.00	0	2	7.53
3	Cutting fore master	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
4	Cutting anchor station	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
5	Cutting Forecastle deck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
6	Cutting Hatch Coming	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
8	Cutting Upper Hull 1 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
9	Cutting Upper Hull 1 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00

10	Cutting Upper Hull 2 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
11	Cutting Upper Hull 2 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
12	Cutting Upper Hull 3 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
13	Cutting Upper Hull 3 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
14	Cutting Upper Hull 4 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
15	Cutting Upper Hull 4 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
16	Cutting Upper Hull 5 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
17	Cutting Upper Hull 5 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
18	Cutting bottom hull 1 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
19	Cutting bottom hull 1 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
20	Cutting bottom hull 2 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
21	Cutting bottom hull 2 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0.00
22	Cutting double bottom 1 starboard	4.00	1.50	3	10.67	12	0.00	0.00	0.00	0.00	0	1	5.44
23	Cutting double bottom 1 portside	4.00	1.50	3	10.67	12	0.00	0.00	0.00	0.00	0.00	1	5.44
24	Cutting navigation deck	6.00	1.50	4	24.00	12	0.00	0.00	0.00	0.00	0.00	2	8.15
25	Cutting double bottom 2 portside	4.00	1.50	3	10.67	12	0.00	0.00	0.00	0.00	0.00	1	5.44

26	Cutting double bottom 2 starboard	4.00	1.50	3	10.67	12	0.00	0.00	0.00	0.00	0.00	1	5.44
27	Cutting bottom hull 3 starboard	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
28	Cutting bottom hull 3 portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
29	Cutting double bottom 3 starboard	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
30	Cutting double bottom 3 portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
31	Cutting bridge deck	6.00	1.50	4	24.00	12	0.00	0.00	0.00	0.00	0.00	2	8.15
32	Cutting bottom hull 4 starboard		0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
33	Cutting bottom hull 4 portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
34	Cutting bottom hull 5 starboard	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
35	Cutting bottom hull 5 portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
36	Cutting boat deck	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
37	Cutting machinery bulkhead	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
38	Cutting 41 starboard	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
39	Cutting 42 portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
40	Cutting 43 starboard	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
41	Cutting 44 portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
42	Cutting upper machinery space starboard	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
43	Cutting upper machinery space portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
44	Cutting upper steering gear	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00

45	Cutting bottom machinery space starboard	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
46	Cutting bottom machinery space portside	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
47	Cutting bottom steering gear	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0	0.00
48	Cutting double bottom 6 starboard	4.00	1.50	3	10.67	12	9	1	8	12.86	0.50	1	26.29
49	Cutting double bottom 6 portside	4.00	1.50	3	10.67	12.00	9	1	8	12.86	0.50	1.00	20.00
50	Cutting double bottom 7 starboard	4.00	1.50	3	10.67	12.00	9	1	8	12.86	0.50	1.00	20.00
51	Cutting double bottom 7 portside	4.00	1.50	3	10.67	12.00	9	1	8	12.86	0.50	1.00	20.00
52	Cutting after peak tank into 2 part	8.5	1.50	6	48.17	12	9	1	8	12.86	0.50	1.00	27.50

Number	Part	Longitudinal Bottom (meter)	smaller plate length		total line cutting (meter)	thickness	penetration			total penetration	total preheat	total reposition	Total Time 4 (minutes)
							number	thickness	time				
1	Primary Cutting Collision Bulkhead	0.00	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
2	Primary Cutting fore peak	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
3	Cutting fore master	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
4	Cutting anchor station	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
5	Cutting Forecastle deck	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
6	Cutting Hatch Coming	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
8	Cutting Upper Hull 1 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00

9	Cutting Upper Hull 1 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
10	Cutting Upper Hull 2 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
11	Cutting Upper Hull 2 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
12	Cutting Upper Hull 3 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
13	Cutting Upper Hull 3 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
14	Cutting Upper Hull 4 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
15	Cutting Upper Hull 4 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
16	Cutting Upper Hull 5 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
17	Cutting Upper Hull 5 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
18	Cutting bottom hull 1 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
19	Cutting bottom hull 1 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
20	Cutting bottom hull 2 starboard	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
21	Cutting bottom hull 2 portside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0.00	0.00
22	Cutting double bottom 1 starboard	6.90	0.50	14	95.22	12	9	0.2	8	35.49	5	14	78.52
23	Cutting double bottom 1 portside	6.90	1.50	5	31.74	12	9	0.2	8	11.83	5	5	31.51
24	Cutting navigation deck	4	1.50	3	10.67	12	9	0.2	8	6.86	5	3	21.63

25	Cutting double bottom 2 portside	6.9	0.50	14	95.22	12	9	0.2	8	35.49	5	14	78.52
26	Cutting double bottom 2 starboard	6.9	0.50	14	95.22	12	9	0.2	8	35.49	5	14	78.52
27	Cutting bottom hull 3 starboard	0	0	0	0	0	0	0	0	0	0	0	0
28	Cutting bottom hull 3 portside	0	0	0	0	0	0	0	0	0	0	0	0
29	Cutting double bottom 3 starboard	6.9	0.50	14	95.22	12	9	0.2	8	35.49	5	14	78.52
30	Cutting double bottom 3 portside	6.9	0.50	14	95.22	12	9	0.2	8	35.49	5	14	78.52
31	Cutting bridge deck	4	1.50	3	10.67	12	9	0.2	8	6.86	5	3	21.63
32	Cutting bottom hull 4 starboard	0	0	0	0	0	0	0	0	0	0	0	0
33	Cutting bottom hull 4 portside	0	0	0	0	0	0	0	0	0	0	0	0
34	Cutting bottom hull 5 starboard	0	0	0	0	0	0	0	0	0	0	0	0
35	Cutting bottom hull 5 portside	0	0	0	0	0	0	0	0	0	0	0	0
36	Cutting boat deck	0	0	0	0	0	0	0	0	0	0	0	0
37	Cutting machinery bulkhead	0	0	0	0	0	0	0	0	0	0	0	0
38	Cutting 41 starboard	0	0	0	0	0	0	0	0	0	0	0	0
39	Cutting 42 portside	0	0	0	0	0	0	0	0	0	0	0	0
40	Cutting 43 starboard	0	0	0	0	0	0	0	0	0	0	0	0
41	Cutting 44 portside	0	0	0	0	0	0	0	0	0	0	0	0
42	Cutting upper machinery space starboard	0	0	0	0	0	0	0	0	0	0	0	0
43	Cutting upper machinery space portside	0	0	0	0	0	0	0	0	0	0	0	0

44	Cutting upper steering gear	0	0	0	0	0	0	0	0	0	0	0	0
45	Cutting bottom machinery space starboard	0	0	0	0	0	0	0	0	0	0	0	0
46	Cutting bottom machinery space portside	0	0	0	0	0	0	0	0	0	0	0	0
47	Cutting bottom steering gear	0	0	0	0	0	0	0	0	0	0	0	0
48	Cutting double bottom 6 starboard	6.9	0.50	14	95.22	12	9	0.2	8	35.49	5	14	78.52
49	Cutting double bottom 6 portside	6.90	0.50	14	95.22	12	9	0.2	8	35.49	0.5	14	78.52
50	Cutting double bottom 7 starboard	6.90	0.50	14	95.22	12	9	0.2	8	35.49	0.5	14	78.52
51	Cutting double bottom 7 portside	6.90	0.50	14	95.22	12	9	0.2	8	35.49	0.5	14	78.52
52	Cutting after peak tank into 2 parts	12.6	0.50	25	317.52	12	0	0.2	8	0.00	0.5	25	71.97

Number	Part	Total time
1	Primary Cutting Collision Bulkhead	30.91
2	Primary Cutting fore peak	30.91
3	Cutting fore master	1.16
4	Cutting anchor station	5.44
5	Cutting Forecastle deck	2.28
6	Cutting Hatch Coming	1.16
8	Cutting Upper Hull 1 starboard	202.53
9	Cutting Upper Hull 1 portside	202.53
10	Cutting Upper Hull 2 starboard	201.45
11	Cutting Upper Hull 2 portside	201.45

12	Cutting Upper Hull 3 starboard	200.94
13	Cutting Upper Hull 3 portside	200.94
14	Cutting Upper Hull 4 starboard	201.45
15	Cutting Upper Hull 4 portside	201.45
16	Cutting Upper Hull 5 starboard	202.10
17	Cutting Upper Hull 5 portside	202.10
18	Cutting bottom hull 1 starboard	195.07
19	Cutting bottom hull 1 portside	195.07
20	Cutting bottom hull 2 starboard	195.07
21	Cutting bottom hull 2 portside	195.07
22	Cutting double bottom 1 starboard	167.69
23	Cutting double bottom 1 portside	120.68
24	Cutting navigation deck	840.98
25	Cutting double bottom 2 portside	89.39
26	Cutting double bottom 2 starboard	90.38
27	Cutting bottom hull 3 starboard	198.81
28	Cutting bottom hull 3 portside	195.07
29	Cutting double bottom 3 starboard	83.95
30	Cutting double bottom 3 portside	83.95
31	Cutting bridge deck	840.98
32	Cutting bottom hull 4 starboard	195.07
33	Cutting bottom hull 4 portside	195.07
34	Cutting bottom hull 5 starboard	195.07
35	Cutting bottom hull 5 portside	195.07
36	Cutting boat deck	2,042.09
37	Cutting machinery bulkhead	181.54
38	Cutting 41 starboard	195.07
39	Cutting 42 portside	195.07
40	Cutting 43 starboard	195.07

41	Cutting 44 portside	195.07
42	Cutting upper machinery space starboard	186.86
43	Cutting upper machinery space portside	186.86
44	Cutting upper steering gear	32.02
45	Cutting bottom machinery space starboard	174.08
46	Cutting bottom machinery space portside	174.08
47	Cutting bottom steering gear	61.48
48	Cutting double bottom 6 starboard	259.89
49	Cutting double bottom 6 portside	246.55
50	Cutting double bottom 7 starboard	246.55
51	Cutting double bottom 7 portside	246.55

APPENDIX 5: Fuzzy Integration

To find the highest risk rank, fuzzy logic approach was conducted. The MATLAB Fuzzy logic toolbox provided an efficient framework for evaluating specific input factors.

1. Fuzzy Rule Based

The Table below highlights the direct relationship between Severity (S) and the fuzzy RPN value. The Fuzzy RPN Value is primarily determined by Severity (S) value, regardless of Occurrence.

Table : Fuzzy rule based

Severity	Occurrence	Fuzzy RPN
VH	VH	VH
VH	H	H
VH	FH	FH
VH	FL	FL
VH	L	L
VH	FL	VL

2. Fuzzification

The fuzzy rules were applied across the six distinct levels for variables S and O. Below is the matrix of combinations in Table 10.9

Table 10. 23: Fuzzification

Severity	Fuzzy RPN Value	Fuzzy RPN
VH	VH	VH
H	H	H
FH	FH	FH
FL	FL	FL
L	L	L
FL	FL	VL

3. Tools and Visualisation

Several MATLAB tools proved invaluable:

- Rule Editor: Allowed the addition of linguistic rules. The given linguistic format input data determined the output parameter's dependency.
- Rule Viewer: Demonstrated the fuzzification process, showing how individual membership function shapes influence the results. Rule viewer is generally used to exhibit the image of the response in the MATLAB Fuzzy interface system. It is also used to demonstrate how the rules are fuzzified and how the individual membership function shapes are influencing the results, as shown in Fig. 6. Figs. 5 and 4 show that one enters inputs through the input edit window and the output is then obtained.
- The Surface viewer helps to view the dependency of the output on one or two of the inputs, such as severity and detection (Rengith & Madhavan, 2018). In this analysis, the presented surface viewer is a three-dimensional mapping view with severity, detection and FRPN. From the plot it was noticed that the maximum amount of dependency of FRPN (142) was obtained for the severity (3) and detection (8) risk indexes

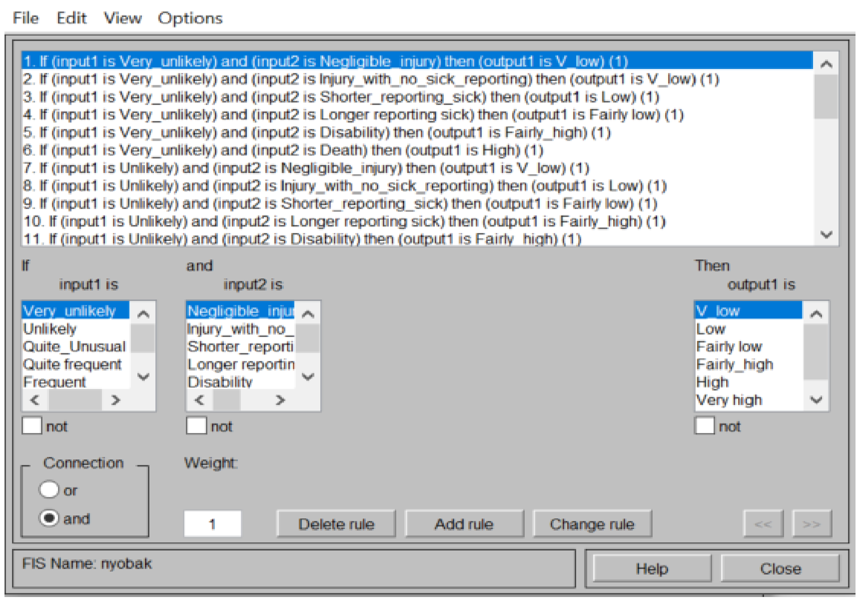


Figure 10. 18: Fuzzy rules

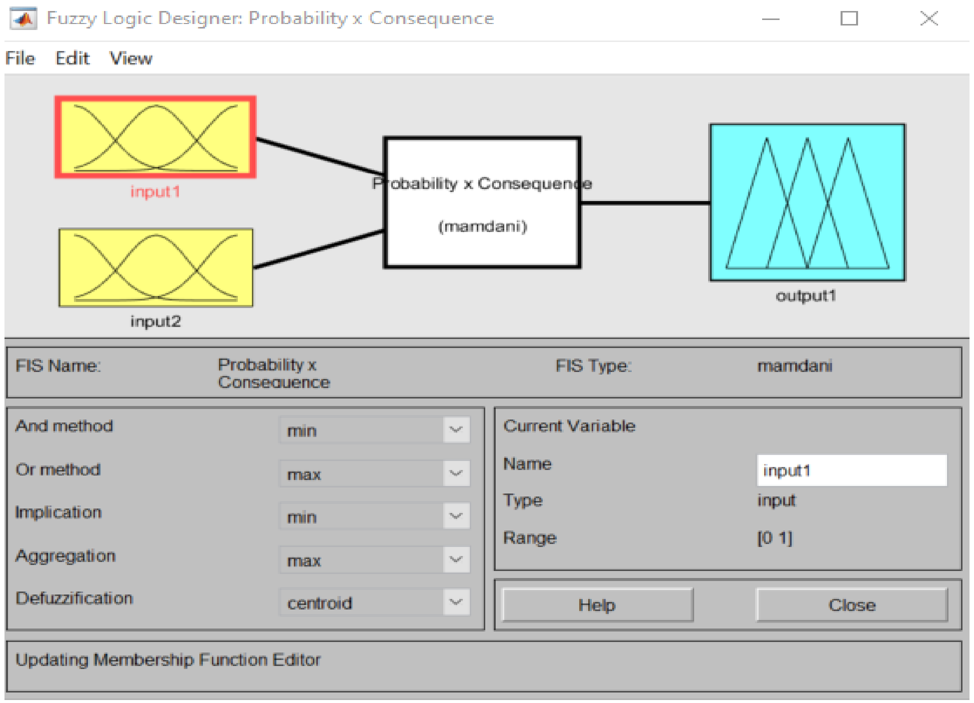


Figure 10. 19: FIS editor

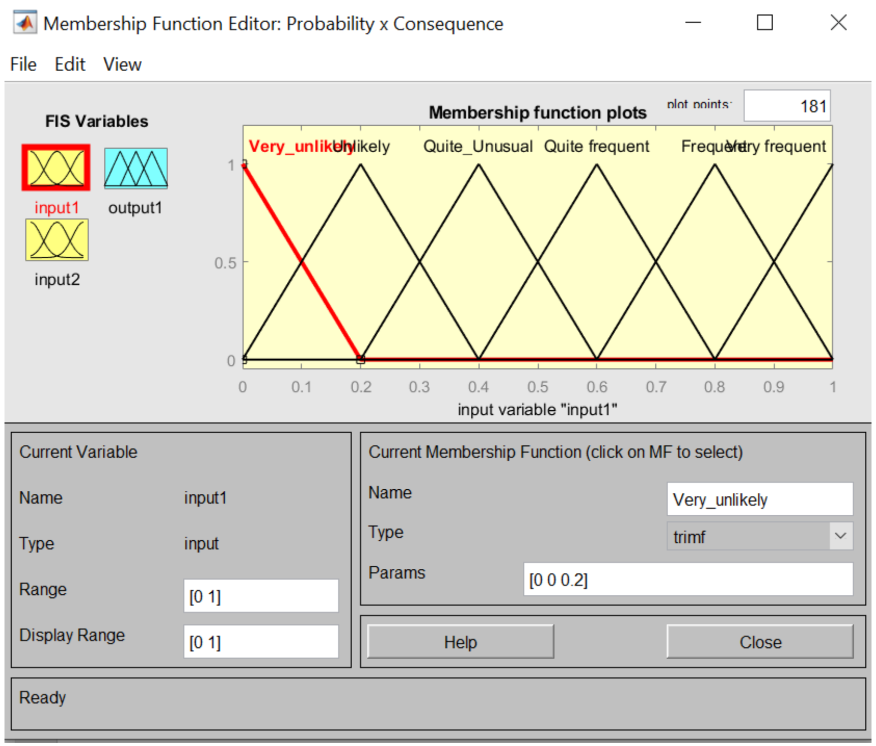


Figure 10. 20: Membership function editor

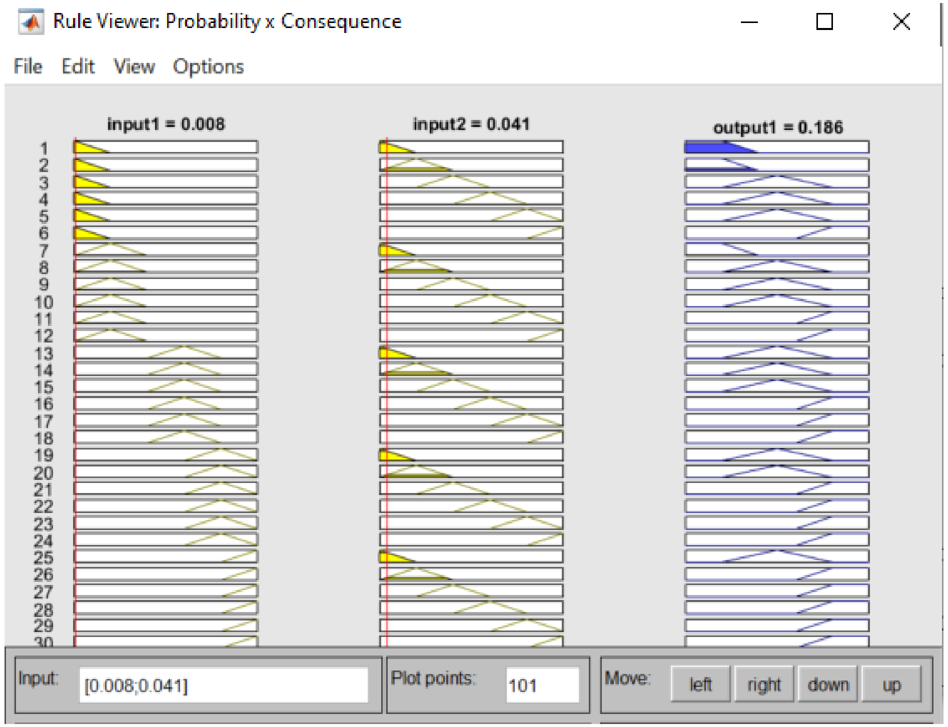


Figure 10. 21: Rule viewer

Surface Viewer: This tool showcased a three-dimensional mapping view with severity, detection, and FRPN. The plot indicated a high dependency of FRPN on severity and detection risk indexes.

4. Result Comparison

The table 10.10 shows the priority ranking based on both the conventional FMEA and the Fuzzy-based FMEA for the analysed machine. The RPN (Risk Priority Number) results, both conventional (C-RPN) and Fuzzy (F-RPN), were established based on the risk indexed parameters: Severity (S), Occurrence (O), and Detection (D).

Notably, the conventional FMEA approach derived its RPN values from the direct product of these risk parameters. In contrast, the Fuzzy-based FMEA utilised the MATLAB Fuzzy interface to obtain the RPN values. A side-by-side comparison between the conventional and Fuzzy RPN values yields interesting insight, Hazard 1.2 (Fire) stands out as the top priority in both methodologies. It has the highest RPN in the conventional approach and remains the most significant concern in the Fuzzy approach.

Table 10. 24: Comparison of conventional RPN and Fuzzy RPN values.

No Hazard	**Conventional**		**Fuzzy**	
	CRPN	Rank	FRPN	Rank
1.1	5	16	0.4	11
1.2	13.46254	1	0.514	1
1.3	6.482759	14	0.32	22
1.4	8.003567	7	0.417	10
1.5	8.489893	6	0.39	13
2.1	6.825208	10	0.418	9
3.1	3.413793	25	0.289	24
4.1	4.344828	23	0.346	18
4.2	4.344828	24	0.346	19
4.3	4.482759	21	0.231	25
5.1	6.806183	11	0.363	17
6.1	6.62069	12	0.325	21
7.1	6.551724	13	0.421	8

8.1	4.448276	22	0.291	23
9.1	7.491082	8	0.431	6
9.2	9.034483	2	0.459	2
10.1	9.034483	3	0.459	3
11.1	8.62069	5	0.439	5
12.1	5	17	0.4	12
13.1	4.586207	20	0.37	16
14.1	4.827586	18	0.389	14
14.2	4.827586	19	0.389	15
15.1	6.183115	15	0.335	20
16.1	7.491082	9	0.431	7
16.2	9.034483	4	0.459	4