Sailing Towards Sustainable Supply Chains: A Multi-Objective Optimization Model for Green Ship Recycling in a Circular Economy

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ABSTRACT

In contemporary global trade, the shipping industry is the cornerstone that facilitates the movement of approximately 90% of international commercial goods. However, environmental challenges, particularly in ship recycling, have become increasingly evident. Over the last few years, worldwide attention to the circular economy has grown to overcome the current production and consumption model based on continuous growth and increased resource throughput. By encouraging the adoption of closed-loop production patterns within an economic system, a circular economy aims to improve resource use efficiency by focusing on urban and industrial waste to achieve better balance and harmony between the economy, environment, and society.

This thesis aims to fill a significant gap in the existing literature on sustainable supply chains, where the predominant focus over the last two decades has been analyzing the methods and risks associated with ship recycling. Notably, there is a conspicuous absence of studies exploring the integration of circularity into the global ship recycling industry. From the sustainability perspective, there is a pressing need for an effective and efficient recovery process for end-of-life products. A key element in this process is a well-executed disassembly that is vital for enabling reuse, remanufacturing, high-value recycling, and the implementation of other circular strategies. This study bridges this gap by delving deeper into the obstacles encountered by the ship-dismantling industry and deriving a solution that benefits both businesses within the industry and the environment. This thesis introduces a new optimization model for a closed-loop supply chain network for the ship recycling industry, integrating reverse and forward logistics. The solution methodology comprises sophisticated techniques for multi-objective mixed integer programming to minimize cost and carbon emissions across the network towards a sustainable future for ship recycling.

Keywords: Circular Economy, Sustainability, Optimization, Ship Recycling, Sustainable Supply Chain, Reverse Logistics, Network Design, Carbon Emissions

LIST OF ABBREVIATIONS

3R	Recycling, Reducing and Reuse
AHP	Analytic Hierarchy Process
BWM	Best Worst Method
CE	Circular Economy
CLSCN	Closed Loop Supply Chain Network
CM	Circularity Market
CSR	Corporate Social Responsibility
CZ	Customer Zone
DC	Disposal Center
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DWT	Deadweight Tonnage
EEA	European Environment Agency
EMF	Ellen MacArthur Foundation
EoL	End of Life
EU	European Union
GA	Gap Analysis
HSE	Health, Safety and Environment
ILO	International Labour Organization
IMO	International Maritime Organization
ISM	Interpretive Structural Modeling
LCA	Life Cycle Assessment
LDT	Light Displacement Tonnage
LE	Linear Economy
MCDM	Multi-Criteria Decision-Making
MFA	Material Flow Analysis

MILP	Mixed-Integer Linear Programming
MPF	Metal Processing Facility
NGO	Non-Governmental Organization
OEM	Original Equipment Manufacturers
PACE	Platform for Accelerating the Circular Economy
PPE	Personal Protective Equipment
QBL	Quadruple Bottom Line
RF	Recycling Facility
RL	Reverse Logistics
RSC	Reverse Supply Chain
SC	Supply Chain
SDY	Ship Dismantling and Assembling Yard
SLR	Systematic Literature Review
SR	Ship Recycling
SSC	Sustainable Supply Chain
SW	Shredder Waste
SWARA	Stepwise Weight Assessment Ratio Analysis
TEC	Total Emissions Costs
TISM	Total Interpretive Structural Modeling
TOC	Total Operational Costs
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VIKOR	VlseKriterijumska Optimizacija I Kompromisno Resenje
WM	Waste Management

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Chapter 1: Introduction

Approximately 90–95% of international commercial goods are transported by sea because of their cost efficiency. Shipping is an international activity because ships sail worldwide and is the most critical link in the global logistical chain of world manufacturers. Thus, the shipping industry represents the smallest part of a product's cost, thus making trade viable. Nevertheless, the shipping industry has potentially negative impacts on the maritime environment and economic disadvantages. In addition, if there is no appropriate integrated system for the recycling or reuse of vessel-related steel, machines, auxiliaries, and furnishings, such materials will remain unused and useless to the economy by the end of the vessel lifecycle (Chang et al., 2010). In Waste Management, the recycling (or "breaking") of EoL ships has long been a highly marginalized topic that has only been addressed by research in recent years. Waste vessels contain large quantities of recyclable components, such as liquid-quenched and softened steels, copper, titanium alloys, aluminum, and electronic equipment with inherent recyclable components (Steuer et al., 2021).

1.1 Problem Definition

Robust engineering structures are designed to withstand harsh conditions, and ships are often contaminated by hazardous pollutants and hydrocarbons. The typical lifespan of ships ranges from 15 to 30 years depending on their type and operational circumstances. Once a ship reaches the end of its productive life, it must be decommissioned, demolished, and recycled. International shipping plays a crucial role in reducing transportation costs in the context of globalized trade and supply chains. However, limited research has been conducted on the End-of-Life stages of decommissioned ships. Nevertheless, End-of-Life ships hold significant potential for economic development and grassroots capacity building, considering that over 1000 ships, totaling nearly 20 million tons of scrap material, are decommissioned each year (Choi et al., 2016). Following ship disposal, the primary focus is on extracting and repurposing steel, which significantly reduces the demand for new steel production and conserves iron resources, while also lowering energy consumption.

Additionally, salvaging parts and other hardware from decommissioned ships is also feasible. The ship recycling industry faces significant environmental and sustainability challenges, primarily because of the traditional linear shipbreaking approach. The linear model results in significant waste generation, resource depletion, and environmental pollution. As the industry seeks to transition towards a more sustainable and resource-efficient approach, circular economy principles have emerged as a potential solution. However, the implementation of circular economic practices for ship recycling is complex, and presents several challenges. Therefore, the problem addressed in this thesis is to examine the barriers and opportunities for implementing circular economy principles in ship recycling and to identify strategies for enhancing sustainability and resource efficiency in the industry.

1.2 Research Questions

The main aim of this study was to answer the following research questions (RQs).

RQ 1) What are the key challenges and barriers to implementing circular economy principles in the ship recycling industry and how can they be effectively addressed?

RQ 2) How do different circular economy strategies such as material recovery, component reuse, and remanufacturing affect the environmental performance and economic viability of ship recycling operations?

RQ 3) What are the key factors influencing the decision-making processes of ship owners and operators when adopting circular economy practices for end-of-life vessels?

RQ 4) How would the implementation of a closed-loop supply chain network benefit the entire economic and environmental system?

RQ 5) How many dismantling yards should be established to minimize all types of cost?

RQ 6) What are the best practices that the ship recycling industry borrows from other industries that have successfully implemented circular economy principles?

RQ 7) How can an optimized CLSCN be developed for the ship recycling industry that integrates both reverse and forward logistics?

RQ 8) What future research areas can further enhance the integration of the circular economy into ship recycling?

These research questions aim to explore various aspects of circular economy implementation in ship recycling, including environmental, economic, social, technological, and policy dimensions. They provide a foundation for an in-depth analysis and investigation of the challenges, opportunities, and potential solutions associated with promoting circular economy principles in the ship-recycling industry. Table 1 lists the locations of the answers to each research question.

Table 1. Mapping of Research Questions and Answers

Chapters	**Research Questions**							
	RQ 1	RQ 2	RQ 3	RQ 4	RQ 5	RQ 6	RQ 7	RQ 8
Ch. 2	✓	✓	✓					
Ch. 3				✓		✓	✓	
Ch. 4		✓		✓	✓			
Ch. 5								✓

1.3 Research Contribution

Table 2 summarizes 16 articles related to EoL materials with an integrated supply chain.

Table 2. Research Papers Comparison

Papers	**Approach**			**Sustainability Dimension**		**Industry/EoL Material**	**Contribution Towards Sustainability**
	MFA	CE	RSC	Environmental	Economic		
(Du et al., 2018; Jain et al., 2016, 2017)	✓			✓	✓	Ship Recycling	Examines the application of multidisciplinary scientific tools and techniques aimed at rendering environmentally sustainable ship recycling economically viable for ship owners while maintaining high standards of HSE practices. The MFA enables ship recycling yards to enhance waste and resource management, leading to cost reduction and improved efficiency.
(Rahman and Kim, 2020)	✓	✓		✓		Ship Recycling	• Explores the global patterns of ship flow, global environmental benefits, and domestic metabolism to gain insights into this issue. • To reduce the exploitation of natural resources, the circular economy strives to promote resource and material circularity as part of its commercial approach. However, achieving circularity poses challenges as recycling operations may not always occur within the same geographical area. Therefore, it is essential to consider the potential negative impacts associated with the specific site where these activities take place to achieve true circularity.
(Du et al., 2017; Steuer et al., 2021; Tola et al., 2023)		✓		✓	✓	Ship Recycling	• Assessing alternative management options for Chinese ship recycling facilities in handling EoL vessels within the framework of the circular economy. • Enhance the existing knowledge by establishing connections between ship recycling, life cycle management activities, and circular economy models. Additionally, introduce a conceptual framework that facilitates the efficient recirculation of components and raw materials within the ship recycling industry.
(Rahla et al., 2021)		✓		✓		Construction	Identify criteria for selecting building elements in alignment with circular economy principles. This will be achieved by conducting a comprehensive review of the latest research in the field.
(Rentizelas et al., 2022)			✓	✓	✓	Wind Turbine Blades	Assess the feasibility of adopting the CE approach through mechanical recycling for reusing EoL blades in composite material manufacturing. The study specifically focuses on optimizing the design of the reverse supply network in Europe.
(Kuşakcı et al., 2019)			✓		✓	EoL Vehicles	This study aims to develop a fuzzy mixed integer location-allocation model for reverse logistic network of ELVs conforming to the existing directives in Türkiye.

Table 2. Research Papers Comparison (Cont.)

Papers	Approach			Sustainability Dimension		Industry/EoL Material	Contribution Towards Sustainability
	MFA	CE	RSC	Environmental	Economic		
(Rentizelas and Trivyza, 2022)		✓	✓	✓	✓	Car Manufacturing	The findings demonstrate that minimizing per unit and overall system costs is achieved by increasing the proportion of remanufactured frames, underscoring the need for designing frames with remanufacturability as a key consideration. The study also highlights the cost reduction potential associated with economies of scale. Furthermore, it is evident that the reusable frame offers environmental and economic advantages compared to the single-use alternative.
(Hiremath et al., 2016; Schøyen et al., 2017)		✓		✓		Ship Recycling	Focuses on the role and influence of international ship-owners in relation to environmental and safety conditions in ship recycling.
(Ahmed et al., 2022)		✓		✓		General	It explores the potential, practices, and challenges of implementing the circular economy model in Bangladesh. Despite the prospects of transitioning to the CE, the study reveals that the applicability of the CE model is highly restricted in Bangladesh, with limited implementation observed primarily in recycling processes within certain industries.
(Lieder and Rashid, 2016; Mauss et al., 2023)		✓			✓	Manufacturing	Gain insight into the application of change management in the transformation processes towards the CE in manufacturing companies. It aims to understand the methods and extent to which change management can be utilized, as well as to identify the distinguishing factors that set the path to circularity apart from other change processes.
(Ghisellini et al., 2016)		✓		✓	✓	Waste Management	It aims to gain a comprehensive understanding of the key features and perspectives of the CE. It explores the origins, fundamental principles, benefits, drawbacks, and the modeling and implementation of CE across various levels (micro, meso, and macro) globally. The results reveal that the origins of CE are primarily grounded in ecological and environmental economics, as well as industrial ecology.
This Thesis		✓	✓	✓	✓	Ship Recycling	The research introduces an optimized CLSCN for the ship recycling industry, integrating both reverse and forward logistics. The proposed solution involves the application of sophisticated techniques, such as MILP, to optimize a comprehensive multi-objective model that minimizes cost and carbon emissions across the network.

1.4 Research Gap

Although growing recognition of CE principles comes from the perspective of ship dismantling, a major research gap must be addressed. Few studies have comprehensively investigated the practical implementation and effectiveness of circular economy practices in real-world ship-dismantling operations. While the concept of CE has gained attention, there is a lack of in-depth research exploring the challenges, opportunities, and outcomes of adopting circular economy principles in ship dismantling. This research gap has hampered the development of evidence-based strategies and guidelines for sustainable ship dismantling. Additionally, there is a need for a comparative analysis across different regions and countries to identify the best practices and learn from successful cases of circular economy implementation. Addressing these research gaps will enhance the understanding of circular economy implementation in ship dismantling, and provide valuable insights for policymakers, industry stakeholders, and researchers aiming to promote sustainable ship recycling practices.

1.4.1 Limited Focus on Practical Implementation

One research gap in the field of circular economy in ship recycling is the limited focus on the practical implementation of circular economy principles in real-world ship-dismantling yards. There is a need for research exploring the challenges and opportunities of implementing circular economic practices in the context of ship recycling operations. This includes exploration of specific strategies, technologies, and business models to facilitate the transition from LE to CE.

1.4.2 Lack of Comprehensive Impact Assessment

Another research gap is the lack of comprehensive impact assessment studies that evaluate the environmental and economic aspects of circular economy practices in ship recycling. While studies have examined specific aspects of circularity, such as material recovery or energy efficiency, there is a need for holistic assessments that consider the overall sustainability performance and trade-offs associated with circular economy initiatives. This includes evaluating the life cycle impacts, cost-effectiveness, and social consequences of implementing CE principles in the ship-recycling industry.

1.4.3 Future Technological Trends and Innovation

The rapid evolution of technology and innovation in the maritime industry presents opportunities for advancing circular economic practices for ship recycling. However, there is a research gap in exploring the potential impact of emerging technologies such as automation, robotics, advanced material identification, and sustainable dismantling methods on the circularity of ship recycling. Investigating these future technological trends and their implications can guide decision makers in adopting innovative solutions and staying at the forefront of circular economy implementation. Closing the identified research gaps will contribute to a more comprehensive understanding of circular economy implementation in the ship recycling industry; address practical challenges; and guide policymakers, consultants, and stakeholders aiming to promote sustainable and circular practices in ship recycling processes.

1.5 Research Motivation

The motivation behind this research is to explore and analyze the potential benefits and challenges associated with the application of CE principles in the ship recycling industry. Ship recycling plays a significant role in the lifecycle of vessels, and involves the dismantling and disposal of ships at the end of their operational lives. However, conventional ship recycling practices often lead to environmental pollution, occupational hazards, and inefficient resource utilization. Therefore, there is a growing interest in adopting circular economy approaches to address these issues and promote sustainable ship recycling practices.

1.5.1 Environmental Concerns

The environmental impact of ship recycling is a major driving force in the promotion of a circular economy in this industry. Conventional practices often result in the release of hazardous substances into the surrounding ecosystem, thereby leading to water and soil pollution. Additionally, the improper disposal of ship components and waste materials contributes to landfill accumulation. By adopting circular economy principles, such as recycling, reuse, and upcycling, it is possible to minimize the environmental footprint of ship recycling activities, reduce pollution, and conserve natural resources.

1.5.2 Economic Opportunities

Circular economy in ship recycling also provides significant economic opportunities. Through efficient waste management and resource recovery, valuable materials and components from decommissioned ships can be recycled or sold, thereby providing a potential revenue stream for the shipbreaking yards. This can contribute to job creation, particularly in regions where ship recycling is a top industry. Moreover, adopting circular economy practices can foster innovation and the development of new technologies and business models, leading to economic growth and competitiveness in the ship recycling sector.

1.5.3 Corporate Social Responsibility

Corporate Social Responsibility has become an integral part of business operations across industries including ship recycling. The adoption of circular economy principles aligns with CSR goals, demonstrating a commitment to sustainable practices, environmental stewardship, and workers' well-being in ship-recycling activities. The motivation to embrace a circular economy in ship recycling stems from the desire to improve working conditions, promote occupational health and safety, and ensure ethical treatment of workers throughout the ship dismantling process. The motivations for exploring the circular economy approach to ship recycling are multifaceted, encompassing environmental concerns, economic opportunities, and social responsibilities. By addressing these motivations and promoting sustainable ship recycling practices, the industry can minimize its environmental impact, maximize resource efficiency, and contribute to a more circular and sustainable economy. This study aimed to provide a comprehensive understanding of these motivations and contribute to the advancement of circular economy implementation in ship recycling. This study aims to provide valuable insights into the motivations for implementing CE principles in the ship-recycling sector.

1.6 Research Methodology

This section outlines the research methodology employed to investigate the circular economy model of the ship-recycling industry. The objective of this study was to provide a future overview of the ship recycling industry and assess the implementation and effectiveness of CE principles in ship recycling processes, considering both economic and environmental aspects. To answer these research questions, an extensive review of scientific studies encompassed both the academic literature and industrial reports on recycling. The first phase in writing the literature review chapter involved a systematic search was conducted to retrieve published studies pertaining to ship recycling activities and circular economy models. This study followed the SLR technique, which employs a methodical, transparent, and replicable methodology to identify and assess significant contributions relevant to a specific research topic (Denyer and Tranfield, 2009). Based on the study by Maestrini et al. (2017), SLR includes four phases: (i) source identification, (ii) source selection, (iii) source evaluation, and (iv) data analysis, as illustrated in Figure 1.

Two databases were used during the source identification step: SCOPUS and Google Scholar. These two databases were selected to ensure a comprehensive and authoritative collection of sources. SCOPUS, a peer-reviewed abstract and citation database, provides access to high-quality academic literature and advanced search tools (Yun and Ülkü, 2023). By contrast, Google Scholar broadened the scope of my research with its inclusive and easily accessible range of scholarly materials, including articles, theses, and conference papers, some of which may not be indexed by other databases. By leveraging the credibility and precision of Scopus along with the accessibility and breadth of Google Scholar, I aimed to establish a well-rounded and robust foundation for my literature review. To increase the number of articles considered in the analysis, meticulous selection of keywords was performed. The following keyword string was used.

(Green OR Sustainable OR Circular Economy OR Reverse Logistics OR Closed Loop Supply Chain Network OR Sustainable Supply Chain) AND (Ship OR Vessel OR EoL Ship OR EoL Vessel) AND (Breaking OR Scraping OR Recycling OR Dismantling)

A manual cross-checking process was carried out, and Mendeley bibliographic citation software was utilized with the "sort by title" method to identify and remove duplicate results. The screening was performed based on the abstracts of the articles. The number of records has decreased from 145 to 95. The following criteria were used to evaluate the remaining records.

- Studies specifically addressing shipyard improvements in ship recycling were also included.
- Studies that contribute to the development of potential sustainable methodologies and circular economy actions for ship recycling were also included.
- Studies that contribute to the CE model in other industries, such as automotive and aviation, were included.

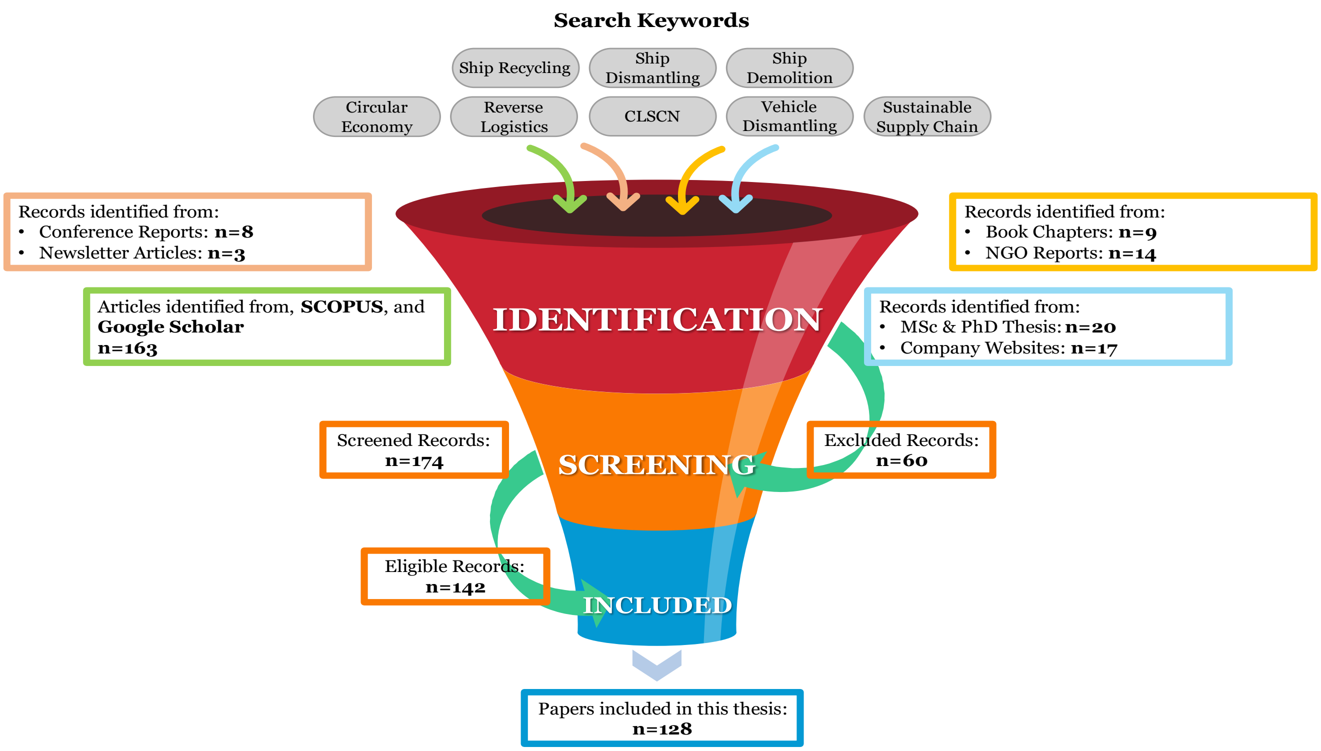


Figure 1. Literature Search and Evaluation Process

The data analysis phase aimed to highlight key activities and summarize relevant findings. Various tools, methods, approaches, opinions, and strategies related to ship recycling are examined and surveyed to provide a comprehensive response to this research question. Figure 2 illustrates the trends in published articles based on specific keyword combinations from 2003 to 2022. The articles focused on various aspects of ship recycling and its intersection with sustainability. The depicted keyword combinations include themes related to circular economy, reverse logistics, closed-loop supply chain networks, and sustainable supply chains. Each keyword combination was distinctly represented through color-coded bars corresponding to the number of publications in different time brackets. A notable observation is the escalating interest in articles that align with the keyword "Ship Dismantling OR Ship Recycling AND Circular Economy." By the 2019-2022 range, there was a surge of 15,100 articles underscoring the growing emphasis on integrating circular economy principles with ship recycling. Conversely, publications encompassing the "End of Life Ship OR Ship Recycling AND Sustainable Supply Chain" keyword demonstrate consistent traction, especially from 2015 onwards. This steady interest implies continued exploration of sustainable supply chain practices in the context of ship recycling. However, the areas of reverse logistics and closed-loop supply chain networks, as reflected by their respective keyword combinations, have witnessed varied publication numbers across the years, hinting at fluctuating academic attention to these specific intersections. The graph aims to track and compare the scholarly interest and attention given to the intersection of ship recycling and various sustainability concepts over the last two decades. This is significant given the growing importance of sustainable practices in industries such as ship recycling.

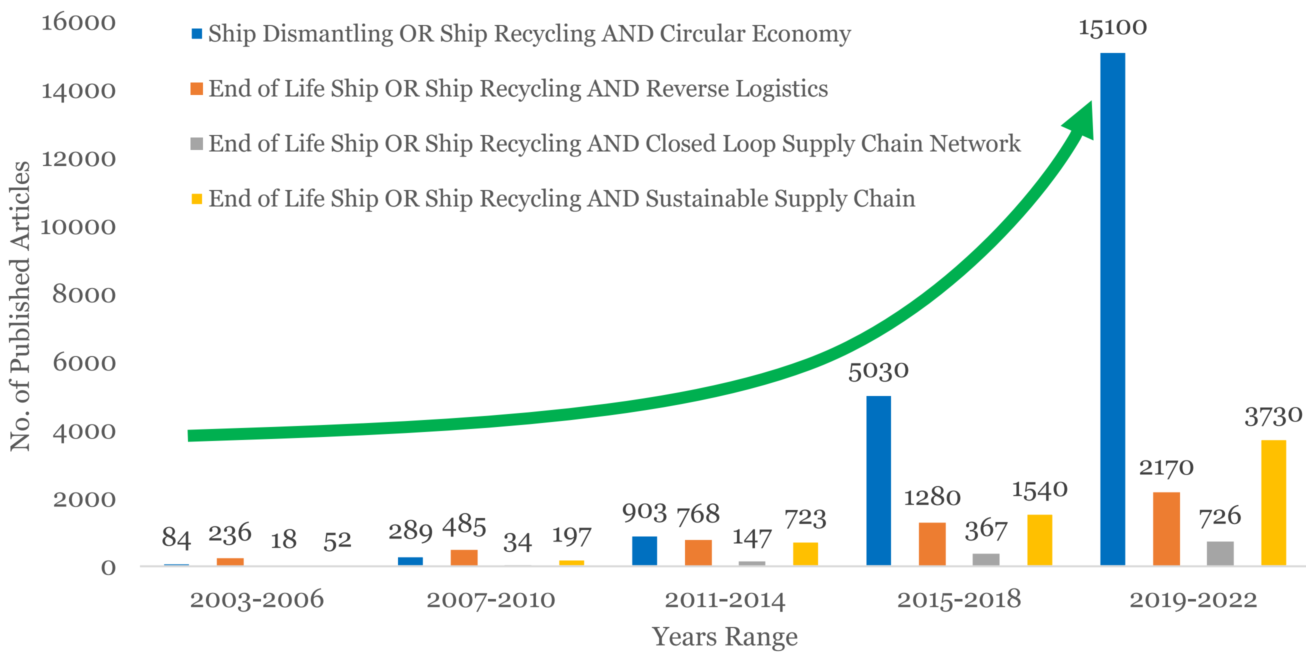


Figure 2. Keywords Trend (Anywhere in the Article) for Searches Ranging Over 2003–2022

1.7 Thesis Structure

This thesis consists of five chapters: Chapter 1 "Introduction" describes the problem definition, research questions, contribution, motivation, and methodology. Chapter 2 "Literature Review" provides an overview of the ship recycling industry and some insights into how CE can be used in the ship recycling industry. Chapter 3 "Problem Formulation and Model" explains the model used in this study. Chapter 4 "Results and Discussion" presents managerial insights and discusses the findings with limitations. Finally, Chapter 5 "Conclusion" summarizes the study.

Chapter 2: Literature Review

Even after commercial use, ships continue to be potential sources of marine and coastal pollution. 'Ship recycling,' as an industry, is also known as 'ship breaking' or 'ship dismantling' (Karim, 2015). The ship recycling industry plays a pivotal role in global trade and the maritime sector, contributing significantly to economic growth. However, this industry has long been associated with environmental and social challenges, leading to an urgent need for sustainable practices (Sivaprasad and Nandakumar, 2013). The process of dismantling an old and non-functional ship to recover and recycle its constituent materials can provide opportunities to reuse recyclable materials (Ozturkoglu et al., 2019). From this standpoint, it represents a cost-effective and environmentally friendly approach for shipowners and developing economies (Dey et al., 2021). However, HSE issues that arise during ship dismantling can lead to environmental and ecosystem pollution, as well as potential injuries to workers (Schøyen et al., 2017). Recently, companies have implemented sustainable supply chain management practices to reduce negative environmental and social impacts within their supply chains. During this period, supply chain literature developed a circular approach to achieve these goals (Mastos et al., 2021). The concept of CE has gained importance as a transformative approach towards achieving resource efficiency and reducing waste (Korhonen et al., 2018).

Recently, many individuals and entities, such as consumers, businesses, governments, and policymakers, have actively engaged in the transition towards a circular economy. To facilitate this transition successfully, it is crucial to establish common objectives that motivate stakeholders to collaborate when designing efficient transformative approaches. Academic research focusing on the circular economy has yielded significant breakthroughs in understanding and managing natural resources, and has provided valuable insights and methodologies (Ren et al., 2023). Globally, companies need to be reformed and natural resources should be managed prudently to reduce waste and establish standardized material recovery practices. Failing to address these aspects poses additional challenges, particularly maintaining sufficient capacity for the reuse or recycling of undesirable items (Schröder et al., 2020). To achieve successful ship recycling, it is essential to develop a closed-loop supply chain that incorporates both the reverse and forward chains. The forward logistics aspect involves the conversion of raw materials from suppliers to final products, which are then distributed to meet customer demands. By contrast, the reverse logistics component focuses on the return of used products from customers to collection centers for repair, remanufacturing, or recycling. Reverse chains can be categorized into two types: closed-loop and open-loop. Closed-loop logistics occurs when the new product market aligns with the returned product market, creating a connected network. However, an open-loop network exists when these two markets do not coincide. In simpler terms, closed-loop logistics refer to the integration of both forward and reverse logistics processes (Özceylan and Paksoy, 2013). According to Gilbert et al. (2017), remanufacturing 50% of a ship hull can reduce the CO2 emissions by 10%. In a study conducted by Jansson (2016) that focused on remanufacturing in the marine industry, several benefits and challenges were identified. Customers can benefit from the availability of more affordable parts than from the manufacturing of new products. Businesses can enjoy improved profit margins through the reduced production costs associated with remanufactured products. From an environmental perspective, remanufacturing contributes to improved environmental performance by reducing the consumption of raw materials, energy, and toxic waste. Finally, remanufacturing in the marine industry can create better employment opportunities, thereby contributing to a more sustainable industry. Table 3 presents the key studies that have developed and formulated logistics networks by integrating the optimization model for various EoL products.

Table 3. Key Studies in EoL Products

Study	**Optimization Model**		**Sustainability Dimension**		**SCN Type**		**Industry/EoL Product**
	MINP	MILP	Environmental	Economic	RL	CL	
(Easwaran & Üster, 2010)		✓		✓		✓	Electronics
(Özceylan and Paksoy, 2013)		✓		✓		✓	General
(Kilic et al., 2015)		✓		✓	✓		Electrical Waste
(X. Zhou and Zhou, 2015)	✓			✓	✓		Office Paper
(Demirel et al., 2016)		✓		✓	✓		EoL Vehicles
(Yi et al., 2016)		✓		✓		✓	Construction
(Liao, 2018)	✓			✓	✓		Furniture
(Kim et al., 2018)		✓		✓		✓	Fashion
(S. T. John et al., 2018)		✓		✓	✓		Refrigerator
(Zarbakhshnia et al., 2019)		✓	✓	✓		✓	General
(Rentizelas & Trivyza, 2022)		✓	✓	✓		✓	Car Sharing
(Rentizelas et al., 2022)		✓	✓	✓	✓		Wind Turbine
This Thesis		✓	✓	✓		✓	**Ships**

Overall, this literature review explores the existing body of knowledge surrounding the circular economy in the context of the ship recycling industry. To gain a complete understanding of CE in the ship recycling industry, it is essential to explore existing literature and research on this topic. This chapter discusses a wide range of sources including academic articles, industry reports, non-government publications, and case studies. This review involves both theoretical frameworks and empirical studies, providing a full view of the current state of knowledge in the field and serving as a critical foundation for subsequent chapters of this thesis. This chapter aims to contribute to the ongoing discourse on sustainability by exploring existing literature.

Table 4. Summary of Publications on the EoL Ships

Paper	Solution Approach							Sustainability Dimension			Study Area			
	MFA	LCA	BWM	CE	RA	Design	WM	Environmental	Economic	Social	Policies and Laws	Worker's Safety	Dismantling Method	Hazardous Materials
(Tewari et al., 2001)					✓			✓				✓		✓
(Srinivasa et al., 2003)							✓	✓						✓
(Basha et al., 2007)							✓	✓						✓
(Florent, 2008)							✓		✓		✓			
(Sonak et al., 2008)							✓	✓	✓					✓
(Moen, 2008)							✓	✓			✓			✓
(Knapp et al., 2008)					✓				✓				✓	
(Chang et al., 2010)							✓	✓						✓
(Carvalho et al., 2011)		✓						✓					✓	✓
(Khan et al., 2012)				✓				✓	✓				✓	
(Neşer et al., 2012)							✓	✓						✓
(Hougee, 2013)					✓			✓			✓			
(Sivaprasad and Kumar, 2013)						✓		✓					✓	
(Muhibbullah et al., 2014)					✓			✓		✓				✓
(Alam and Faruque, 2014)						✓		✓			✓			
(Cairns, 2014)					✓			✓						✓
(Kurt, 2015)					✓					✓		✓		
(Hiremath et al., 2015)							✓	✓						✓
(Rahman and Mayer, 2015)	✓									✓		✓		
(Nøst et al., 2015)					✓			✓						✓
(Frey, 2015)					✓					✓	✓		✓	
(Jain et al., 2016)	✓							✓	✓					✓
(Yılmaz et al., 2016)					✓			✓						✓
(Hossain et al., 2016)					✓			✓					✓	✓
(Hiremath et al., 2016)					✓			✓				✓		
(Argüello Moncayo, 2016)						✓		✓		✓	✓			
(Devault et al., 2016)					✓			✓	✓				✓	
(Jansson, 2016)				✓				✓	✓				✓	
(Choi et al., 2016)					✓			✓	✓				✓	
(Devault et al., 2017)					✓			✓	✓				✓	✓
(Ignacio Alcaide et al., 2017)					✓					✓	✓			
(Sujauddin et al., 2017)	✓								✓					✓
(Schøyen et al., 2017)					✓			✓				✓		
(Gilbert et al., 2017)		✓						✓					✓	

Table 4. Summary of Publications on the EoL Ships (Cont.)

Paper	Solution Approach							Sustainability Dimension			Study Area			
	MFA	LCA	BWM	CE	RA	Design	WM	Environmental	Economic	Social	Policies and Laws	Worker's Safety	Dismantling Method	Hazardous Materials
(Gilbert et al., 2017)		✓						✓					✓	
(Jain et al., 2017)	✓							✓						✓
(Jain et al., 2017)	✓							✓						✓
(Barua et al., 2018)					✓			✓						✓
(Barua et al., 2018)					✓			✓						✓
(Du et al., 2018)					✓			✓						✓
(Gunbeyaz et al., 2019)					✓					✓	✓	✓		
(Ocampo and Pereira, 2019)						✓		✓					✓	
(Misra, 2019)					✓					✓		✓		
(Ozturkoglu et al., 2019)					✓			✓						✓
(Rizvi et al., 2020)						✓		✓				✓	✓	
(Singh et al., 2020)					✓			✓				✓		✓
(Hsuan and Parisi, 2020)						✓		✓	✓		✓			
(Rahman and Kim, 2020)	✓							✓						✓
(Gunbeyaz et al., 2020)						✓		✓					✓	
(Devaux and Nicolaï, 2020)						✓				✓	✓			
(Steuer et al., 2021)				✓				✓	✓				✓	
(Soner et al., 2021)			✓					✓					✓	
(Önal et al., 2021)	✓							✓					✓	
(S. M. M. Rahman et al., 2021)					✓			✓					✓	
(Zhou, Liang, et al., 2021)					✓					✓		✓		
(Zhou, Du, et al., 2021)				✓				✓					✓	
(Tanha et al., 2022)						✓		✓			✓	✓		
(Gunbeyaz et al., 2023)					✓					✓		✓		
(Tola et al., 2023)				✓				✓					✓	

Two decades ago, the management of EoL ships was in its early stages; however, it evolved into a well-established and expanding research field. Table 4 presents a summary of 56 articles related to EoL ships published over the past two decades. It shows a comparison between the papers based on three main categories: the solution approach, sustainability dimensions, and study area.

The proper management of EoL ships is a critical issue that affects various stakeholders such as governments, producers, treatment facilities, and users. The implementation of regulations and new laws has become even more important from both the environmental and economic perspectives.

Table 4 elucidates the diverse array of methodological approaches employed in the literature, ranging from MFA to LCA, illustrating the breadth of the research techniques deployed to evaluate sustainability in the context of EoL ships. In the initial decade of the study, the scholarly focus was predominantly on waste management practices, subsequently shifting towards the incorporation of risk analysis methods. The consistent emphasis on the management of hazardous materials across the corpus of research underscores the need to address the safe and responsible handling of toxic substances inherent in EoL vessels. In addition, despite the hazardous nature of ship dismantling, relatively few studies have focused on worker safety during the first decade; however, attention has increased in the second decade. Furthermore, economic considerations are regularly examined, reflecting the significant costs entailed in ship recycling and broader economic ramifications for the maritime sector. The literature exhibits a bifurcation in research methodologies, with certain studies pursuing a comprehensive approach that encompasses a multitude of sustainability dimensions and study areas, while others maintain a targeted focus on specific elements. This dichotomy of research interests suggests a spectrum of scholarly inquiries encompassing both holistic assessments and specialized, focused investigations.

2.1 Ship Recycling Industry Overview

Each ship has three phases: "(i) designing and building as asset creation, (ii) shipping operations as upkeep, and (iii) EoL dismantling" (Tola et al., 2023). When vessels reach the end of their functional lifetime, they are commonly retired through various methods, such as ship scrapping, disarmament, abandonment, shipbreaking, and recycling. Among these methods, recycling is often considered to be the most preferable approach for ship disposal because it offers numerous advantages and is regarded as the optimal choice. Mannan et al. (2023) stated that out of the eleven ship recycling methods available, four are widely recognized and commercially practiced as shipbreaking methods. These include beaching, along-side/afloat, slipways, and dry docking.

On the other hand, there are additional methods, such as artificial reefing, hulking, SINKEX, ship museums, scuttling, wreck diving sites, and ship donation programs, which are considered ship recycling methods but are not conventional or commercially prevalent. Traditionally, ship recycling has been deeply ingrained, with shipbreaking playing a fundamental role in financing the industrial revolution for a considerable period. Occasionally, ship recycling or shipbreaking is referred to as ship dismantling, disposal, or scrapping. During the World War II, nations like the US, the UK, and

Germany constructed a specific class of ships known as the "obsolete fleet." With the decommissioning of these vessels, a new industry emerged called "Obsolete Vessel Scrapping," driven by engineering advancements and shifts in global socioeconomic dynamics. Initially, during the mid-20th century, the ship-breaking industry operated predominantly in ports where obsolete fleets were concentrated. However, in the 1950s, ship demolition gradually shifted to the Mediterranean coasts of Spain, Italy, and Japan (Charter, 2017). Prior to the 1960s, ship demolition was primarily focused on developed nations, such as the US, the UK, and Germany. However, in the 1970s, there was a notable shift in ship demolition activities towards emerging nations such as Spain, Türkiye, and Taiwan. This shift was primarily driven by factors such as the availability of low-cost labor forces and the presence of a thriving steel re-rolling industry in these countries. From the early 1980s onwards, ship owners began opting to send their end-of-life ships to ship-breaking yards in India, Pakistan, Bangladesh, the Philippines, and Vietnam to maximize their profits, despite the relatively lower HSE standards prevalent in these nations (Tola et al., 2023).

Ship recycling refers to the disassembly of ships to extract and recover materials for reuse, particularly steel (Hsuan and Parisi, 2020). The ship recycling industry has become a vital phenomenon in the shipping industry when ship owners encounter reduced revenue at the EOL of a vessel. According to records from the NGO Shipbreaking Platform (2022), 443 EoL ships were sold to scrap yards in 2022 (Figure 4). Of these, 292 large tankers, bulkers, offshore platforms, and cargo and cruise ships broke down on the beaches of Bangladesh, India, and Pakistan, accounting for more than 80% of global gross tonnage dismantled. Despite the European Union possessing a significant number of ship demolition yards, only a relatively small proportion of the ships sent for scraping make their way to the coasts of Europe (Tola et al., 2023). According to Wan et al. (2021), an extensive analysis of more than 22,500 business records of ships scrapped between 2000 and 2019 revealed that 22,547 ships were dismantled globally, resulting in a dismantling of approximately 357,365,473 GT.

Ship owners recycle their vessels in South Asian shipbreaking nations, mainly developed countries (Figure 4). It is attractive to ship owners because they benefit from low labor costs and loose health, safety, and environmental regulations. Scrap resources are also being supplied to the construction industry (Rahman and Kim, 2020). These locations possess favorable geographic, economic, and labor conditions, attracting shipowners seeking cost-effective dismantling services. However, the environmental and social challenges associated with shipbreaking practices have led to increased scrutiny and efforts towards achieving sustainable ship recycling. Figure 3 shows the number of dismantled ships and their average age. During the last 7 years, we have had a decrease in the number of ships that dismantled and on the other hand. The average age of the ships increased from 26 to 34 years.

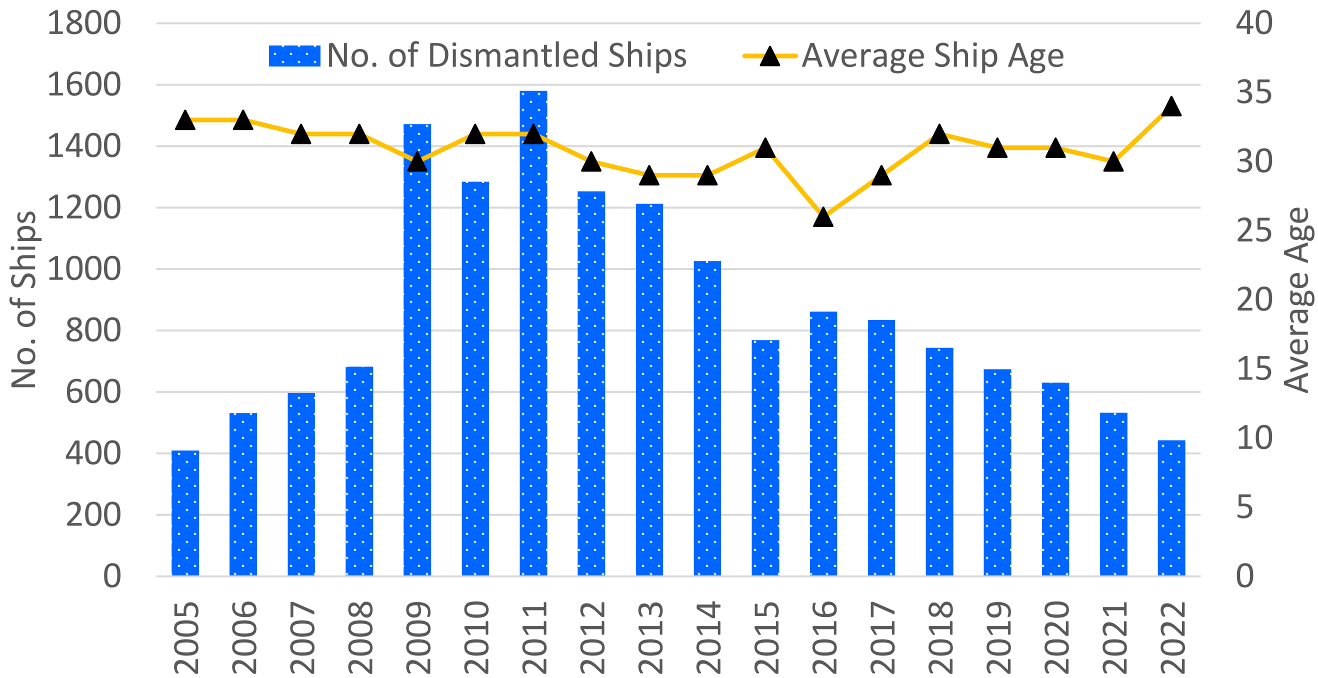


Figure 3. Ship Dismantling Activity in the World from 2005 to 2022
Data Source: https://shipbreakingplatform.org/annual-lists/

The ship recycling industry serves as a crucial link in the life cycle of ships, allowing for the recovery of valuable materials such as steel and providing employment opportunities in numerous coastal regions around the world. However, conventional ship recycling practices often result in negative environmental impacts, including the release of hazardous substances, soil and water pollution, and destruction of fragile ecosystems. Moreover, the working conditions in many shipbreaking yards have been a cause for concern, with reports of labor rights violations and occupational health and safety hazards. Consequently, there is a growing consensus among stakeholders that the ship recycling industry must transition to a more sustainable and circular approach.

Figure 4 illustrates the distribution of ships slated for recycling across various global regions. Countries and regions are denoted on the world map, and each is marked by a circle representing the number of ships. The degree of color is directly proportional to the number of ships in that region. The map underscores a significant concentration of ship recycling activities in South Asia, particularly in India and Bangladesh. These two nations alone account for a combined total of 249 ships, significantly outweighing the number in other regions. This observation aligns with the established understanding that ship recycling has shifted towards developing nations due to economic considerations and less stringent regulatory environments.

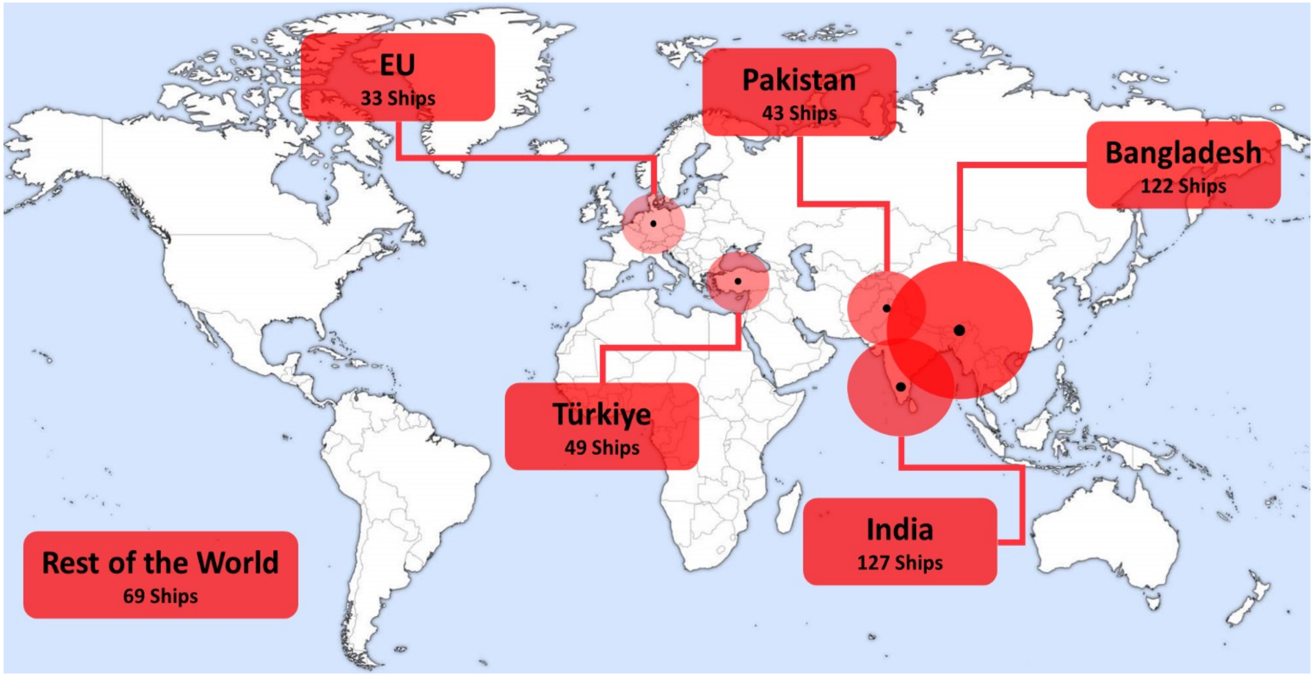


Figure 4. Shipbreaking Records in 2022 (Number of Ships)
Data Source: https://www.offthebeach.org/2022/

Ship recycling costs are relatively higher in the European Union and the USA than in Asia because of the strict environmental and occupational safety and health regulations. Thus, ship-recycling facilities in the EU and USA are not economically sustainable. The shipping industry relies on developing countries to disassemble decommissioned vessels via recycling. Consequently, the ship recycling industry avoids the burden of complying with the high-cost standards in developed countries to manage the hazardous waste involved in decommissioning (Chang et al., 2010). Figure 5 shows the number of ships recycled between 2016 and 2022. Although most ships are owned and operated by high-income economies, such as the EU, the United States, South Korea, and Japan, a significant portion (approximately 80%) is dismantled in just three countries: Bangladesh (32%), India (28%), and Pakistan (19%).

The widely criticized beaching method strands ships along the coast, where they are disassembled into smaller sections by unskilled workers, with minimal protection. This practice often exposes delicate coastal zone environments to hazardous materials released during the dismantling process (Wan et al., 2021). There was a visible decline in the total number of ships dismantled after 2018, indicating either a decrease in EoL ships or an increase in regulations and environmental concerns that could limit shipbreaking activities. Notably, the EU has the least contribution, reflecting stricter environmental regulations and more advanced ship recycling facilities. The fluctuations in numbers for India and Pakistan suggest varying economic or regulatory factors that influence their shipbreaking industries annually.

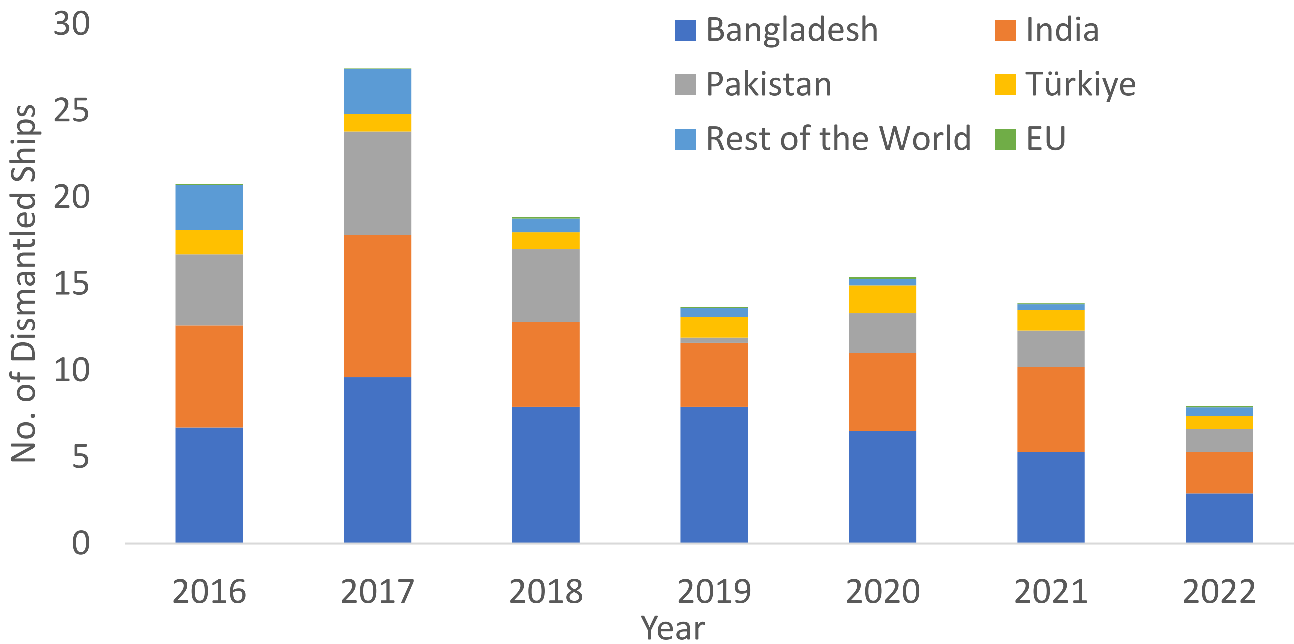


Figure 5. Comparison of Ship Dismantling in Different Countries
Data Source: https://shipbreakingplatform.org/annual-lists/

Several vital stakeholders have emerged to extend a product's life. Shipping operators (shipping companies or ship owners) function as decision makers to purchase services such as maintenance, repairs, and improvement of existing ships ordering and selling vessels in the circularity market (CM) and selling vessels to a disassembling yard. Shipyards and associated subcontractors are field service providers who conduct maintenance, repair, and retrofitting of ships and supply spare parts when necessary. OEMs are responsible for facilitating access to technical input and services (Milios et al. 2019). The ship-recycling industry encompasses the disposal and dismantling of various types of vessels that have reached the end of their operational lives.

Figure 6 provides a detailed breakdown of ship recycling activities by type and country for 2022. This chart illustrates not only the geographic distribution of ship recycling, but also the types of ships that are more likely to be recycled, owing to their size and the profitability of reclaimed materials. From the graph, we can infer that certain countries specialize in handling heavy/big ships, whereas others specialize in dealing with smaller vessels or low-duty ships. Different factors, such as recycling methods, recycling yard capabilities, and countries' regulations regarding ship recycling. For example, Türkiye primarily specializes in passenger ships. Bangladesh focuses on bulk carriers, chemicals, and oil tankers. The minimal involvement of the EU could point to stringent environmental regulations that either limit the capacity for recycling within the region or render it economically unviable compared to its South Asian counterparts.

Understanding the characteristics and components of these ships is essential for evaluating the challenges and opportunities associated with the recycling processes. The following paragraphs provide a brief explanation of each vessel type: Cargo ships, including bulk carriers, container ships, and general cargo ships, comprise a significant proportion of vessels recycled worldwide. The ships transport goods, commodities, and other materials. Their large size and complex structure present unique challenges for recycling. Materials, such as steel, engine components, and navigation equipment, can be recovered and reused.

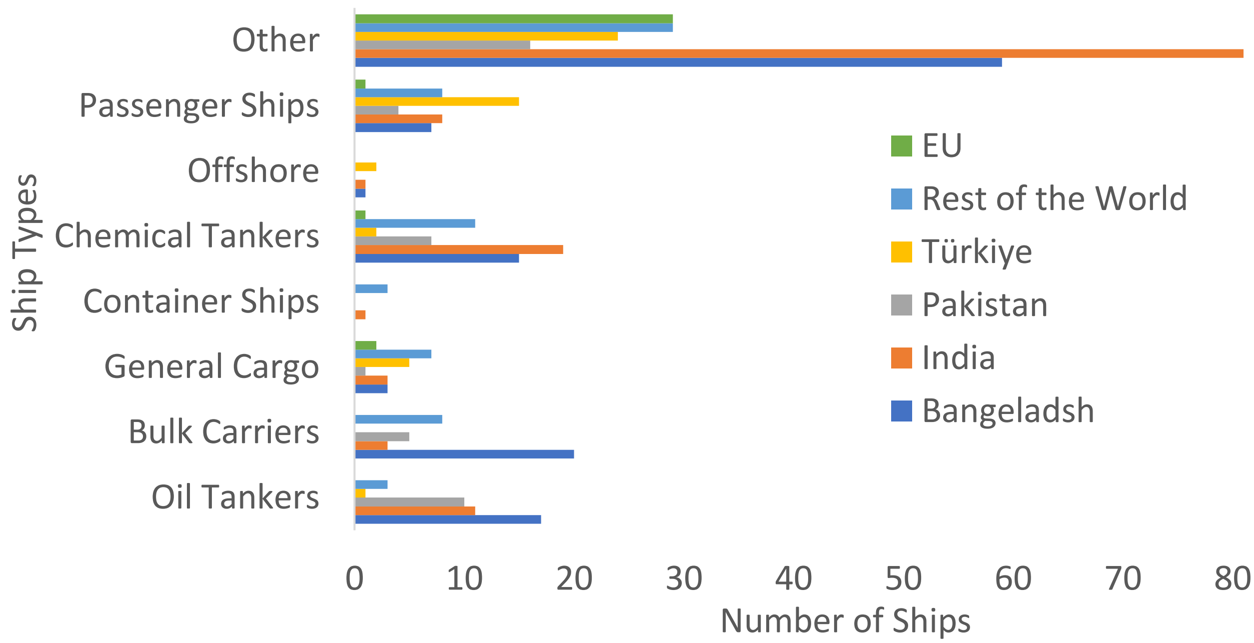


Figure 6. Global Ship Recycling Activities by Country and Ship Type in Year 2022
Data Source: https://shipbreakingplatform.org/annual-lists/

Tankers such as oil and chemical tankers are another category of frequently recycled ships (Figure 7). Because of their function in transporting hazardous substances, tankers require specialized dismantling procedures to ensure the safe handling and disposal of residues. The recycling of tankers offers opportunities for the recovery of valuable materials such as steel and non-ferrous metals. Passenger ships including ferries and cruise liners are commonly retired and recycled. These ships are often equipped with luxury amenities and advanced systems, which can be recovered and repurposed. However, the presence of hazardous materials such as asbestos and heavy metals requires careful handling to mitigate environmental and health risks. Offshore structures, such as drilling rigs, production platforms, and fishing vessels are also recycled at the end of their operational lives. These vessels and structures contain valuable materials and equipment including steel, electronics, and machinery, which can be reclaimed for further use. Category other, which is explained in the above chart, contains specialized vessels, such as research vessels, icebreakers, and naval ships, which also undergo recycling processes. These vessels often contain sensitive equipment, classified technology, and hazardous materials, which necessitates adherence to strict regulations and security protocols during recycling.

Figure 7. Main Ships Typologies
Source: © Wikipedia; International Chamber of Shipping; Vroon Website; Marine Insight

Garmer et al. (2015); Hiremath et al. (2015, 2016); Singh et al. (2020) stated in their article the ship recycling know-how practiced in Alang, India ship recycling yard. Figure 8 shows the ship recycling process chart, supported by the inputs and outputs of each process. Hiremath et al. (2015) said it typically takes around 2 to 3 months (depending on the size and complexity) to dismantle and recycle a single ship at this yard. The process starts with inspection, preparation, and certification, primarily comprising docking of the EoL ship to the shore and obtaining clearance from various relevant Regulatory Authorities. It then begins by obtaining permission to beach the vessel. In this step, the ship moves closer to the yard and is thoroughly scrutinized by customs officers and regulatory authorities. Only after receiving approval from these authorities is the ship beached along the Alang coast for dismantling and recycling. The third work activity includes the cleaning and draining of oil and fuel tanks and disconnecting lubricant lines. Initially, all the fuel tanks were identified and thoroughly inspected. Customs officers destroy navigational equipment on the board.

The recovery of unused and partially spent materials was then initiated. In this step, any unused or partially spent material was identified and recovered (Hiremath et al., 2015). In the fifth step, the safety officer inspects the bilge water tanks, after which the bilge water is pumped and gathered in dedicated tanks in transport vehicles. The collected bilge water was then transported to a designated hazardous waste treatment storage and disposal facility in Alang. At this facility, bilge water is treated using an activated sludge process, and the resulting treated water is utilized for gardening purposes. Subsequently, the fire safety officer confirmed that the ship was safe to cut and permitted ship cutting. The seventh step involved the recovery and sale of usable materials from a dismantled ship. Finally, the yard manager auctioned all sellable materials. This is followed by the task of extracting all reusable materials from a ship that are temporarily stored within the yard before being transported to their respective buyers (Singh et al., 2020).

The ship recycling industry deals with a diverse range of ship categories, each of which requires specialized approaches and considerations. Cargo vessels, tankers, passenger and cruise ships, offshore structures, and specialized vessels present unique challenges and opportunities for recycling. Understanding the composition, materials, and specific requirements of each ship type is crucial to ensure safe, efficient, and environmentally friendly dismantling processes. By implementing appropriate practices and regulations tailored to the characteristics of each ship category, the ship recycling industry can effectively address the environmental, social, and economic aspects associated with the retirement and recycling of these vessels.

2.1.1 Decision Factors

Ship owners and stakeholders in the maritime industry face complex decisions regarding vessel recycling. This section explains the key factors that influence ship recycling decisions. Understanding these factors is crucial for effective decision-making and promoting sustainable practices in the ship recycling industry. As shown in Figure 11, ship owners decide whether to recycle a ship for four main reasons (Jain and Pruyn, 2017). These factors control the demand and supply dynamics of vessel recycling and freight markets, because most ships taken out of the freight market are supplied to the ship recycling market.

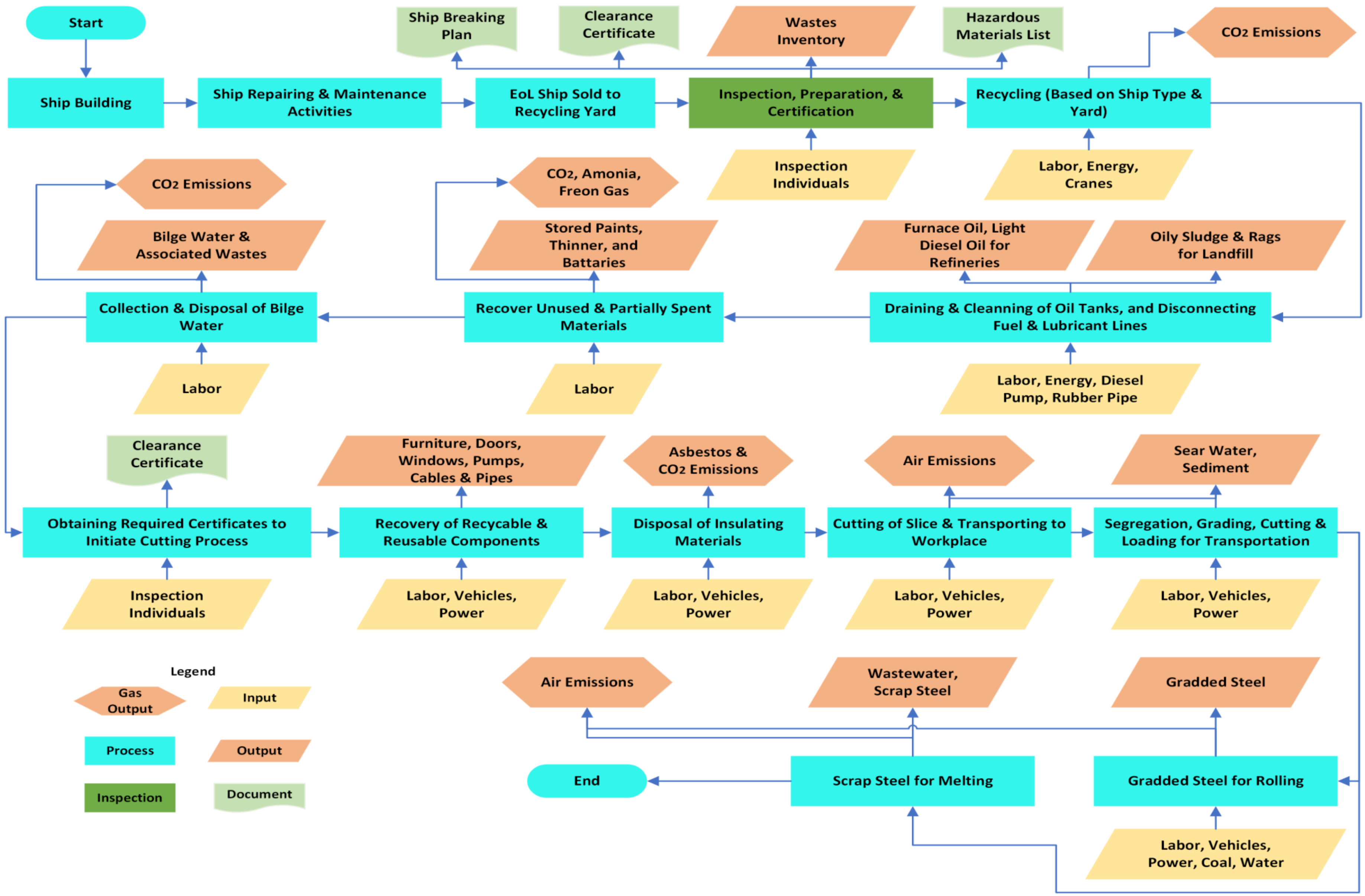


Figure 8. Ship Recycling Procedures in Alang, India
Source: Based on (Garmer et al., 2015; Hiremath et al., 2015, 2016; Singh et al., 2020)

2.1.1.1 Current Earnings

In addition to the clear indicators of low earnings, the market may also be depressed. Consequently, ship owners rely on two crucial factors–current earnings and future market expectations–to determine whether to keep a ship active in the shipping industry (Zhou et al., 2021). Low earnings caused by high operational expenses or low freight rates lead to a decline in the profitability of vessel operations. This necessitates ship owners to implement specific cost-saving measures such as slow steaming, temporarily laying up ships, and converting vessels for alternative trades. Once all cost-cutting measures have been exhausted, ship owners are faced with two primary options: first, to continue operating in the market despite incurring losses, with the hope that freight rates will improve soon; and second, to sell the ship either in the circularity market for continued trading under a different owner or in the ship recycling market for dismantling and recycling.

2.1.1.2 Ship's Obsolescence

Several factors, such as physical, technical, and regulatory, control the ship's obsolescence. Thus, a wide range of ship ages sent for recycling were observed in the datasets recorded for ship recycling. For example, Jain and Pruyn (2017) reported that the average age of ships sent for scrapping was approximately 25–30 years. Figure 9 shows the average dismantling age for various types of ships from 2012 to 2022, which tends to have a longer lifespan when it comes to demolition, owing to several factors, such as facing less intense competition, receiving better maintenance, and being easier to adapt. Over the past decade, there has been noticeable volatility in the average age at which ships are dismantled, which is affected by factors such as fluctuating market demand, advancements in maritime technology, and regulatory changes impacting ship longevity. Oil tankers and bulk carriers displayed relatively high average dismantling ages, indicating that these vessels were utilized for longer periods because of their significant initial investment and operational viability. In contrast, the dismantling age for container ships, passenger ships, and other categories shows more fluctuation, suggesting that these vessels may be subject to faster turnover owing to technological obsolescence or changing market conditions.

The physical obsolescence of ships owing to aging is a natural process that occurs gradually. As a ship ages, its body and machinery wear and tears increase. Therefore, ship owners must spend more money on routine repair and maintenance of older ships, making them more expensive (Zhou et al., 2021). The repair and maintenance costs were high, particularly during the fourth and fifth surveys. Special surveys were conducted every fifth year to renew the class certificate of the ship. This includes an out-of-water inspection of the ship hull to verify its structural integrity and conformance with its systems, machinery, and equipment with applicable class rules. Docking is usually expensive in terms of both cost and foregoing income. Physical obsolescence is the process of the deterioration of a ship's hull and machinery to such an extent that it becomes unworthy of repair (Jain and Pruyn, 2017).

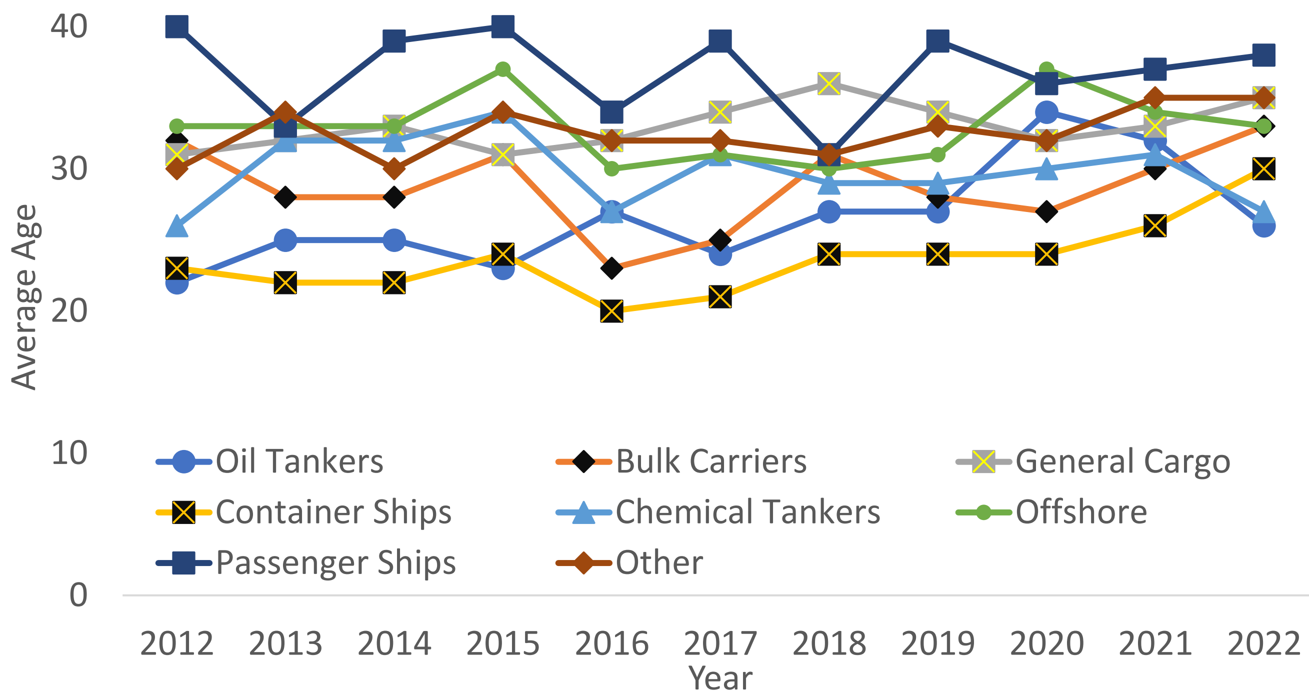


Figure 9. The Average Dismantling Age for Various Types of Ships
Data source: https://shipbreakingplatform.org/annual-lists/

Technical obsolescence is indicated by a ship that, despite being physically sound, is no longer profitable to remain in service because of the increased competitiveness of a more efficient ship type. Scrapping vessels according to regulatory requirements is defined as regulatory obsolescence. For example, a ship may be out of service because of an oil tanker, which can lead to massive oil spills and irreparable environmental damage (Chang et al., 2010; Dey et al., 2021).

2.1.1.3 Scrap Price

Scrap prices do not play a vital role in the ship owner's decision on when to scrap a ship as much as deciding where to scrap a vessel (Zhou et al., 2021). A ship operating unprofitably, with no expectation of being profitable shortly, is likely to end up in a ship recycling yard for scrapping even at a low scrap price. Nevertheless, the decision to scrap a ship can be slightly delayed if an increase in scrap prices is anticipated in the short term. A ship recycling yard that offers a high price to an EoL ship is always attractive to shipowners. Figure 10 shows the demolition price (USD/LTD) relative to the number of dismantled tanker ships in the Indian market. When the number of dismantled ships increased, the price also increased, as is clearly shown during the two periods from Jun-16 to May-18 and Jun-20 to Nov-21. As can be clearly seen in Figure 10, the demolition price experienced fluctuations over the years, with a noticeable downward trend between mid-2018 and early 2020 and a subsequent sharp increase, peaking around the end of 2020. After Nov 2021, both the demolition price and the number of ships dismantled exhibit a declining trend, emphasizing the cyclical nature of the industry and the responsive relationship between price and the number of ships scrapped.

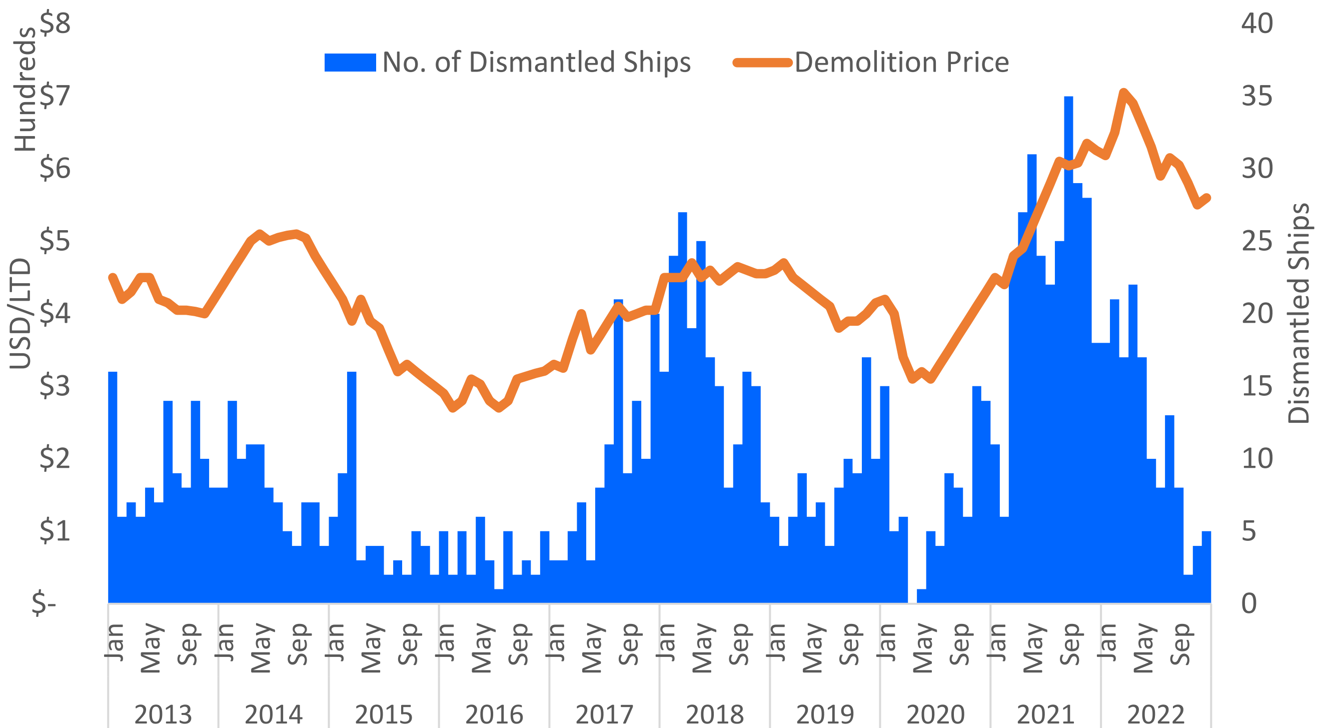


Figure 10. Tanker Ship Demolition Price, Vs Scrapped Ships in the Indian Market
LDT: The displacement of a ship without cargo, fuels, stores, and crew
Data Source: https://www.vesselsvalue.com/reports/ Retrieved in Feb 2023

The determination of the offer price for EoL ships is influenced by the fundamental economic concepts of supply and demand on a global scale. Within the ship demolition market, the supply of obsolete ships is shaped by shipowner decisions regarding vessel scrapping. However, a broader economic perspective reveals that the pricing of EoL vessels is anchored in the principles of demand and supply. The inflow of obsolete ships earmarked for scrapping forms the supply, whereas the demand is steered by the steelmaking industry's appetite for scrap steel. Local factors significantly influenced the offer prices of EoL ships. These factors include adherence to health, safety, and environmental standards in ship recycling yards; the intended use of scrap steel (melting or re-rolling); market demand for other recyclable items such as non-ferrous scrap, used machinery, and furniture; labor wages; costs associated with waste disposal; taxes; and the chosen method of recycling (beaching, slipway, alongside, drydock). Additionally, several other factors affect the offer price, such as the distance between the ship's last port of call and the recycling yard, contractual terms and conditions such as "on delivery" and "as-is, where-is," the complexity of the hull configuration, the ship's compatibility with the recycling yard in terms of size and draft restrictions, and the presence of remaining items on board, including bunkers, waste oil, and spare parts (Jain and Pruyn, 2017).

2.1.1.4 Future Market Expectations

Ship owners may rationalize their choice to continue operating an unprofitable vessel during an economic downturn by anticipating higher freight rates in the future. This decision is justified by the potential for substantial earnings during a period of booming freight rates, which can offset losses incurred during a market downturn (Jain et al., 2016). However, if a ship owner foresees a prolonged period of lower freight rates, they may be compelled to sell their ship. The decision to opt for the recycling market rather than the circularity market is based on the ship's selling potential and value in the circularity market. When the scrap value exceeds the market value, or when there is a lack of buyers in the circularity market, the ship is likely to be sold in the recycling market (Zhou et al., 2021).

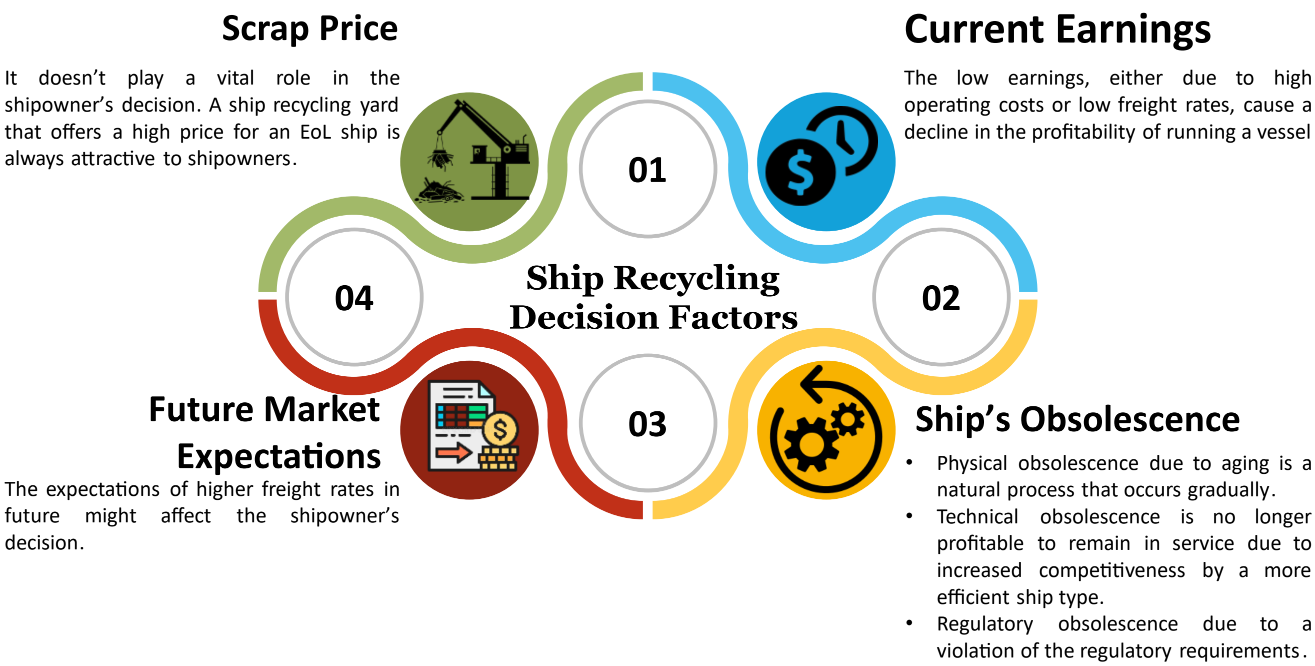


Figure 11. Ship Recycling Decision Factors

2.1.2 Industry Stakeholders

The ship recycling industry involves various stakeholders who play critical roles in its functioning. These stakeholders can be broadly categorized into three main groups: shipowner nations, recycling yards, and regulatory groups (Rahman and Kim, 2020). Ship owners are among the primary stakeholders in the ship-recycling industry. They are responsible for making decisions on the disposal of EoL ships. Ship owners can include shipping companies, individual ship owners, or financial institutions that have acquired ships through foreclosure or lease termination. Their main considerations revolve around maximizing economic returns, complying with environmental regulations, and managing the reputational risks associated with the recycling process (Rahman and Mayer, 2015).

Recycling yards, also known as shipbreaking yards, are crucial stakeholders involved in dismantling and recycling EoL ships. These yards specialize in the safe and environmentally sound disposal of ships, focusing on the extraction and recycling of valuable materials, such as steel, non-ferrous metals, and equipment (Devaux and Nicolaï, 2020). They employ a significant number of workers and often operate in geographical regions known for ship recycling, such as Alang, India; Chittagong, Bangladesh; and Gadani, Pakistan (Rahman, 2017). These yards face scrutiny regarding labor conditions, worker safety, and environmental impact, prompting an increasing emphasis on adopting sustainable and responsible practices. Regulatory groups play a vital role in overseeing and enforcing regulations within the ship recycling industry. International organizations such as the IMO and ILO have established guidelines and conventions to ensure safe and environmentally friendly recycling practices (Ozturkoglu et al., 2019). National governments and regional authorities have enacted laws and regulations regarding ship recycling activities within their jurisdictions. These regulations cover aspects, such as worker safety, environmental protection, hazardous material management, and documentation requirements for ship recycling.

Other stakeholders, including financial institutions, insurance companies, classification societies, NGOs, and industry associations also play important roles. Financial institutions provide funding for ship recycling activities, whereas insurance companies assess and manage risks associated with ship recycling operations (Zhou et al., 2021). Classification societies provide technical expertise and ensure compliance with safety standards. NGOs and industry associations contribute to advocacy efforts, promote sustainable practices, and foster collaborations among stakeholders. The ship recycling industry is complex and involves a diverse range of stakeholders, who work together to address the economic, environmental, and social challenges associated with EoL ship disposal. Collaboration and adherence to regulatory frameworks are essential for ensuring sustainable and responsible ship recycling practices (Moncayo, 2016).

2.1.3 Procedures and Methods of Ship Recycling

Ship recycling procedures are of utmost importance in ensuring safe, efficient, and environmentally responsible dismantling and disposal of EoL ships. As the global fleet continues to expand and ships reach the end of their operational lives, proper procedures are necessary to manage associated economic, environmental, and social challenges (Zhou et al., 2021). Figure 12 presents a summary of the ship recycling procedures. In the process of disassembling the superstructure and deck, the dismantling procedure involves systematically deconstructing the superstructure using a top-down approach, proceeding from the outer sections towards the inner components. The cutting operation was performed along the welding lines while taking necessary precautions to safeguard the oil tanks from potential sparks. For oil pipes, the dismantling process commences by disassembling the connections at the flanges using a cold dismantling technique, thus strictly avoiding any gas cutting methods that may pose risks (Du et al., 2017).

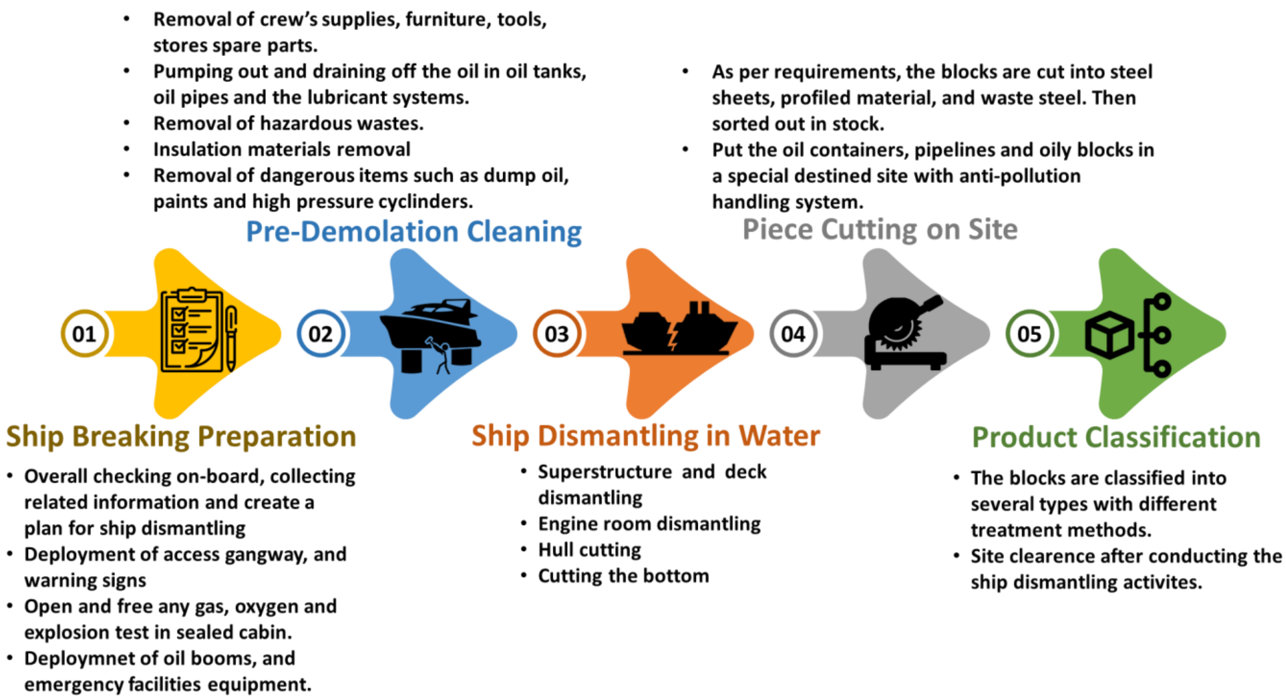


Figure 12. Ship Recycling Procedures Summary

There are several systematic procedures to adhere to when disassembling an engine room. First, a thorough inspection was performed to verify the presence of flammable and explosive items, and the pressure tanks were discharged properly (Du et al., 2018; Muhibbullah et al., 2014). Subsequently, residual oil, gas, or water within the equipment, containers, and pipes was drained. The initial phase of disassembly involves dismantling the connection pipes and various equipment components. When equipment is intended for reuse, it is dismantled along with its base structure (Du et al., 2018). A comprehensive gas-free examination was conducted before initiating the fire-cutting processes. Cold disassembly techniques have been employed to dismantle oil pipes (Gunbeyaz et al., 2023; Soner et al., 2021). However, stringent safety measures must be implemented if fire-cutting is necessary in specific scenarios. The overall dismantling procedure follows the consistent principle of progressing from easy to difficult tasks, from smaller to larger components, and from the top to bottom sections. Throughout the process, efforts were made to maintain a ship balance, ensure timely recycling, and maintain clear pathways for easy access. Importantly, engine room dismantling is performed simultaneously on both sides, rather than on a single side, and cutting operations are strictly prohibited at multiple locations within the same horizontal position (Du et al., 2017).

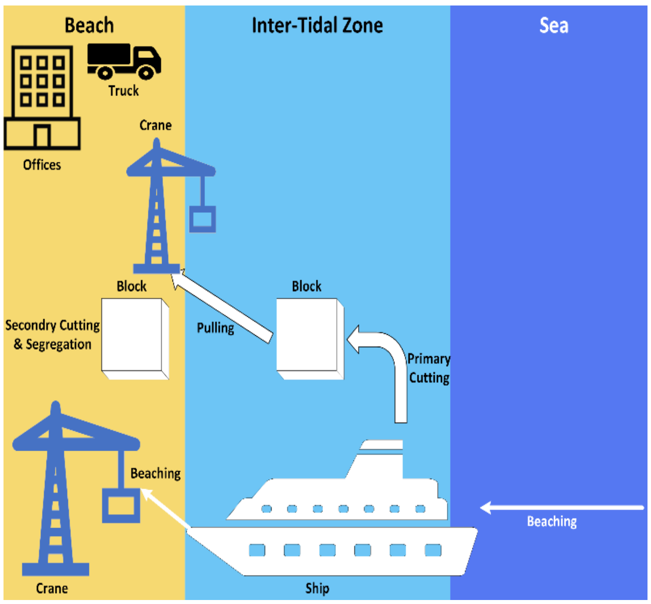
The hull cutting process involves a systematic approach initiated from both the forward and aft sections, followed by the middle section (Chang et al., 2010; Sivaprasad and Nandakumar, 2013). It is crucial to prioritize the dismantling of transverse components before addressing longitudinal components. Throughout the operation, it is essential to maintain a balanced distribution between the port side and the starboard, as well as the forward and aft areas. The simultaneous cutting of longitudinal components within the same section is strictly prohibited to prevent the ship from sinking because of structural failure (Gunbeyaz et al., 2020). The hull is systematically divided into manageable blocks that are promptly transported ashore. Ventilation is particularly important when cutting cabins to prevent lead poisoning. This includes implementing visible warning signs, providing appropriate PPE, ensuring proper training and supervision, and implementing other relevant safety measures (Du et al., 2017).

Finally, when cutting the bottom, it is important to maintain an adequate freeboard height to ensure the buoyancy and longitudinal strength. Once the bottom section was transferred to the floating dock, thorough cleaning was performed to remove any remaining oily sludge and debris. Subsequently, the bottom is divided into manageable blocks and lifted ashore. Ship recycling procedures have been implemented to ensure the safe, efficient, and environmentally responsible disposal of EoL ships. The proper implementation of these procedures is vital for protecting worker safety, mitigating environmental impacts, and promoting sustainable practices within the ship-recycling industry. By adhering to international and national regulations, conducting comprehensive hazardous material assessments, and implementing best practices throughout the ship recycling lifecycle, stakeholders can contribute to the advancement of sustainable ship recycling practices. The ship recycling industry plays a crucial role in the sustainable management of EoL ships, ensuring the recovery and reuse of valuable materials while minimizing the environmental impact. Ship recycling methods are crucial for determining the efficiency, safety, and environmental impact of the recycling process. Various ship recycling methods are classified according to ship docking, including beaching, landing (or non-tidal beaching), alongside (or pier-side breaking), and dry docks.

2.1.3.1 Beaching Method

A significant portion of the existing studies on shipbreaking or ship recycling methods have primarily focused on commercially viable approaches, particularly the beaching method (Figure 13-a). It is the most prevalent ship recycling technique, and is performed during high tide by bringing the ship at full speed to the beach. Approximately 66% of the world's EoL ships are dismantled using this method (Jain and Pruyn, 2017). This is a substandard ship recycling method. “On average, the labour cost of beaching is $11 per ton of ship recycled and can be as low as $6 in Bangladesh.” (Hsuan and Parisi, 2020) Once beached, the ship is gradually dismantled using manual labour and basic cutting equipment. It is cost-effective and labor-intensive; however, it poses significant environmental and safety concerns owing to the lack of infrastructure and appropriate waste management systems.

Owing to their significant tidal range and extensive mudflats, the ship recycling yards in Chittagong, Bangladesh; Alang, India; and Gadani, Pakistan mainly use this technique (Rahman, 2017). India has the world's largest ship-recycling yard located in Alang (Figure 13-b). This yard accounts for 47% of all EoL ships recycled worldwide, and employs nearly 60,000 people (Singh et al., 2020). A potential concern when dismantling ships on tidal mudflats is that any oil or remaining cargo spill may be carried away by the next tide, which poses a significant challenge. However, this can be mitigated by implementing appropriate measures and adhering to appropriate procedures (Jain and Pruyn, 2017).



a) **Beaching Method Scheme**

b) Satellite Image of Beach at Alang, India in May 2023 (Source: maps.google.com)

Figure 13. Beaching Method Scheme and Satellite Image of Beach at Alang, India in May 2023

2.1.3.2 Landing Method

Another method with a higher environmental impact and worker safety is the 'landing method,' also known as the 'slipway method,' which is commonly used in Türkiye because it has a low tidal difference (Figure 14). About 4% of the world's recycling capacity uses it (Jain and Pruyn, 2017). In contrast to the beaching method, ships are pushed towards and pulled up onto a concrete shipway, facilitating the containment of spills and the subsequent clean-up processes. No steel plates, blocks, or other equipment are cut down to the waterline, and at least a portion of the ship remains on dry land with a concrete sloping (slip) (Hougee, 2013). Usually, hull and machinery pieces are removed from a ship by a mobile crane working from the shore. We must admit that the low tidal difference and improved access to the hull and working area offer advantages for safe and environmentally sound operations compared to the beaching method. Safety and environmental concerns arise from the use of slipways as they angle the ship, may impose impracticable working conditions, and there is no full containment (Jain and Pruyn, 2017).

Figure 14. EoL Ships Beached at a Turkish Recycling Yard on a Slipway
Source: https://shipbreakingplatform.org/our-work/the-problem/Türkiye/
© Ship Recyclers' Association of Türkiye

2.1.3.3 Alongside Method

Similarly, in terms of environmental protection, but safer for workers, is the practice of 'alongside,' which constitutes the most practiced method in the USA, the EU, and China. It is also known as 'quayside,' or 'pier side'(Hougee, 2013; Jain and Pruyn, 2017). Thus, ships were docked along a quay to disassemble them by using machines on land (Figure 15). The ship is systematically dismantled using cranes and a choice between automated cutting equipment such as mechanical shears or gas cutting torches. The process follows a "top-down" approach, where the superstructure and upper sections are initially removed, followed by progression through the ship towards the engine room until only the double bottom remains. This method ensures a planned and structured dismantling process (Jain and Pruyn, 2017). In the final step, the remaining body is lifted out of the water for the final dismantling of land or floating dry docks. The fluid leakage flowing into the water can be contained (via oil booms) and subsequently removed. Finally, using dry and floating docks constitutes the cleanest and safest means of ship recycling, the probability of polluting the adjacent environment is relatively low, and the danger of working accidents is significantly reduced (Jain and Pruyn, 2017; Steuer et al., 2021).

Figure 15. Wan Hai 165 Ship is Docked Alongside for Recycling
Source: (The Maritime Executive, 2023)

2.1.3.4 Dry Dock Method

Finally, the most popular method in the EU (NGO Shipbreaking Platform, 2022) is called the 'dry dock method,' in which ships are disassembled in a dry dock, floating dock, or slipway with a locked gate and waterproof floor structure (Figure 16) (Hougee, 2013; Jain and Pruyn, 2017). The dock area is equipped with cranes and additional arrangements as per the established ship recycling facility plan. To ensure stability, the ships were supported by blocks and positioned on the floor in accordance with a predetermined docking plan (Hougee, 2013). This is the safest and cleanest way of recycling a vessel, because the chance of polluting the surrounding water by accident is almost zero, as everything is contained within the dock. The dock was cleaned before flooding to disassemble the next ship and avoid contaminant accumulation. The only negative aspect of this method is that it is expensive to recycle a vessel, which makes it difficult to use (Jain and Pruyn, 2017). According to the latest list of ship dismantling facilities published by EUR-LEX (2022), Denmark, France, Italy, Latvia, the UK, Norway, Finland, and the Netherlands are countries that use the drydock method.

As mentioned previously, ship recycling methods play a fundamental role in the sustainable management of EoL ships. Each method offers a unique set of advantages and disadvantages in terms of the cost, efficiency, worker safety, and environmental impact (Table 5). The choice of method depends on factors such as ship size, availability of infrastructure, compliance with regulations, and the market demand for recycled materials. As the industry moves towards more sustainable practices, the adoption of advanced ship recycling technologies holds promise for further improving the safety and environmental performance of ship recycling operations.

Figure 16. Ships Dismantling in Dry Dock Yard in Rotterdam, The Netherlands
Source: https://shipbreakingplatform.org/our-work/the-problem/eu-row/ © DAMEN

Table 5 vividly emphasizes that no single recycling method is perfect across all the metrics. While some methods prioritize safety or cost-effectiveness, they might compromise yard cleanliness or environmental impact, and vice versa. The industry's challenge lies in optimizing these methods or innovating new ones to enhance both safety and environmental friendliness, while remaining economically viable.

Table 5. Ship Recycling Methods Summary

Comparison Items	Beaching	Landing "Slipway"	Alongside "Pier Side"	Dry Dock
Facility Location	India, Pakistan, and Bangladesh	Türkiye	EU, USA, and China	UK and EU
Ship Type	All Types	Cargo & Oil Tanker	Container & Bulk Carrier	Passenger & Small Ships
Safety	●○○○	●●○○	●●●○	●●●●
Cost	●○○○	●●○○	●●●○	●●●●
Yard Cleanness	●○○○	●●○○	●●●○	●●●●
Pollution	●●●◐	●●◐○	●◐○○	◐○○○

2.1.4 EoL Ship Material Composition

The quantity of waste generated in a shipyard depends on various factors including the number, size, and type of vessels being recycled. Additionally, the recycling percentage can be influenced by factors such as the material composition of the ship, technology employed during the recycling process, market demand for reusable or recyclable products, and pertinent legislation in place (Tola et al., 2023). The ship recycling process produces two types of materials, classified according to their physical characteristics and treatment, as recyclable metallic and non-metallic materials. The types of treatments can be divided into standard procedures and non-recyclables with special treatments. The amount of non-metallic waste generated from ship recycling was low, ranging from 2% to 5% of DWT. The largest proportion of ships (70% to 85% of the DWT) corresponds to metallic materials. This volume varies according to vessel type, ranging from 60% to 70% for bulk carriers, tankers, and general cargo ships. Other materials and equipment that do not correspond to rolled steel are resold in the local and regional shipyard markets. In the case of rolled steel and reversible scrap, the material is sent to local steelmakers where it is re-rolled, or to mills where it is cast and converted into new steel products (Ocampo and Pereira, 2019).

According to a study conducted by Jain et al. (2017), which focused on a 11044T lightweight Handymax bulk carrier, the table below illustrates the flow of materials within the bulk carrier along with the respective sources for each material stream (Table 6). Ship recycling involves cutting substantial sections of the hull of a vessel, which are subsequently transported to land for further dismantling. The overall recycling procedure can be categorized into three primary phases: pre-cutting, cutting, and post-cutting. Every phase of the ship recycling process constitutes a distinct operation as it involves some form of transformation. The pre-cutting phase included a range of surveys and preparations conducted on the hull to facilitate gas cutting. During the cutting phase, the actual process of dividing the steel hull and machinery is divided into smaller fragments. In the post-cutting phase, the materials were sorted and segregated. Further examination of each of these processes can reveal additional subprocesses that occur within them (Jain et al., 2017).

Furthermore, it is worth emphasizing the materials treated during the pre-cutting subprocess. These include minerals, joinery, electrical and electronic wastes, plastics, liquids, chemicals, and gases. Cumulatively, they represent a relatively small portion of the LDT, but their complex nature warrants meticulous handling. Electrical and electronic wastes, as well as chemicals, can pose environmental and safety challenges if not appropriately managed. The material composition of EoL ships is diverse and complex, encompassing various components, such as the hull, superstructure, machinery, electrical systems, piping, and interior fittings. Each component may consist of different materials, including steel, aluminum, copper, plastics, rubber, glass, and various alloys. Analyzing the composition of these materials is crucial for effective waste management, recycling, and sustainable practices in the maritime industry. By understanding the types and quantities of materials present, stakeholders can develop appropriate recycling strategies, assess environmental impacts, ensure the proper handling of hazardous substances, and promote economic viability. Ultimately, this knowledge supports the transition towards a circular economy.

Table 6. Material Composition of a 11044T Lightweight Handymax Bulk Carrier

No.	Material Stream	Quantity (% of LDT)	Output of
1	Ferrous Scrap	84.6	Cutting Sub-Process
2	Machinery	6.18	Cutting Sub-Process, 50% of machinery is assumed reusable and 50% as scrap
3	Minerals	2.52	'Pre-Cutting' Sub-Process
4	Joinery	1.28	'Pre-Cutting' Sub-Process
5	Electrical And Electronic Waste	1.24	'Pre-Cutting' Sub-Process
6	Plastics	1.19	'Pre-Cutting' Sub-Process
7	Non-Ferrous Scrap	1.04	Cutting Sub-Process
8	Liquids, Chemicals, And Gases	1.03	'Pre-Cutting' Sub-Process
9	Miscellaneous	0.92	Cutting Sub-Process

2.2 Green Ship Recycling

The ship-breaking industry is green because it allows for the reuse and recycling of scrap metals and other machinery. This helps conserve natural resources and reduce pollution. The recycled materials can then be used to support national economic activities such as industrialization, construction, and building and infrastructure development (Khan et al., 2012). Green ship recycling has emerged as a critical approach to address the environmental and social challenges associated with the disposal of EoL ships. As the maritime industry seeks to adopt sustainable practices, conventional ship recycling methods, which often result in pollution and worker safety hazards, are being replaced by environmentally friendly alternatives. Green ship recycling focuses on minimizing the ecological impact of ship dismantling, maximizing the recovery of valuable materials, and ensuring the health and safety of the workers (Schøyen et al., 2017; Seroka-Stolka, 2014).

Many countries have expressed concerns about the pollutants generated during ship disassembly and have proposed a green ship recycling concept. In addition, the ship owner's decision to select a recycling yard to disassemble an EoL vessel is primarily guided by the ship price. The recycling yards proposing 'green' recycling services usually quote lower prices than other yards due to the higher cost of disassembling a vessel by following the international ship recycling regulations and

HSE management systems. Such 'green' recycling yards must either lower their costs or increase their revenues to offer better prices to ship owners than to the yards with non-existent HSE standards (Jain et al., 2017). The 'green' ship recycling yards are not very common among many ship owners due to their inability to offer a better price than those that recycle ships in dangerous conditions to the environment and workers. Such yards can become competitive only when the price gap between 'green' and 'non-green' recycling yards is reduced (Seroka-Stolka, 2014). This can only be achieved by increasing revenue and reducing the costs of green ship recycling yards. These yards need to reduce or close the current price gap between 'green' and 'non-green' ship recycling to support environmentally friendly 'green' ship recycling. They must either increase the revenue or decrease the recycling costs of ships. The price gap must be reduced without affecting HSE standards or considering future international regulations on ship recycling, such as the Hong Kong Convention and EU ship recycling regulations (Jain et al., 2017). One way for 'green' recycling yards to reach this objective is to adopt specific scientific tools and techniques used in similar but advanced industries such as aircraft and car recycling. Nevertheless, differences owing to the large size, various types, extensive age range, infrequent supply, and dynamic composition of vessels make it challenging to use the same advanced tools applied in other recycling industries (Jain et al., 2016).

Most production and manufacturing sites reduce costs and increase profit margins by analyzing and optimizing their processes using the principles of operation management. Jain et al. (2017) Stated that vessel recycling could be considered a production system that supports the recovery, processing, and resale of materials and components at the end of a vessel's useful life. Consequently, the tools and techniques used within different production systems should be analyzed for their applicability in the vessel recycling industry. While such operations management tools might reduce the costs of 'green' ship recycling, they must be combined with the analytical tools used in environmental engineering to overcome the challenges faced by the 'green' ship recycling industry regarding environment-related issues. For example, EoL vessels contain all types of hazardous materials that must be handled suitably to avoid harm to the environment, health, and the safety of workers. The complexity of vessels in terms of the structural arrangement and use of several materials is also challenging (Schøyen et al., 2017).

The concept of green ship recycling represents a shift towards sustainable and environmentally responsible practices in the disposal of EoL ships. It acknowledges the need to minimize the negative impact on the environment, enhance resource recovery, and prioritize the health and safety of workers involved in the recycling process (Sivaprasad and Nandakumar, 2013). Green ship recycling embraces principles such as the reduction of hazardous substances, proper handling and disposal of waste materials, and promotion of recycling and reuse of ship components. By adhering to these principles, green ship recycling aims to create a circular economy within the maritime industry, in which materials from decommissioned vessels are recovered and reintegrated into new products or processes. This concept is significant for promoting sustainability and ensuring a cleaner and safer future for ship recycling.

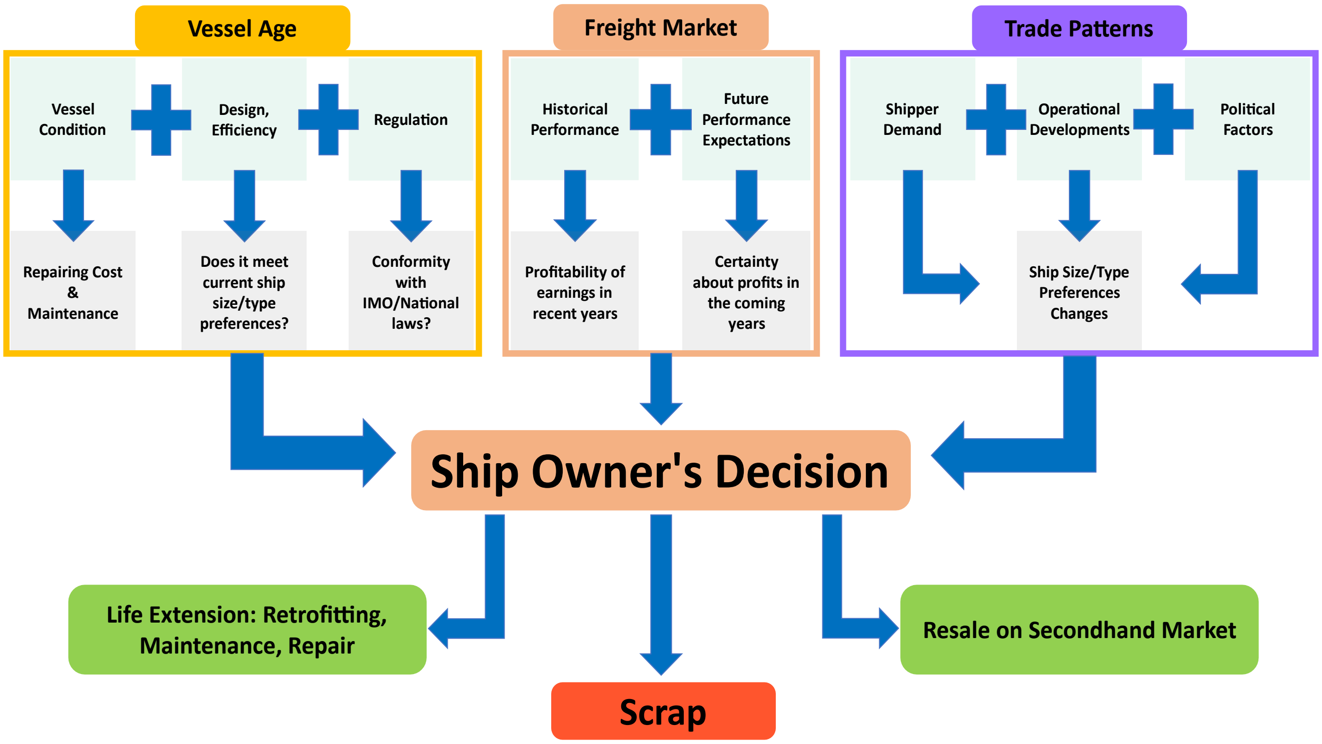


Figure 17. EoL Ship Decision Process

Figure 17 shows the EoL decision-making process of ship owners based on various influencing factors. The ship's age, condition, design, efficiency, and compliance with international and national regulations steer the owners' decisions. Within the context of the freight market, historical performance, anticipated future profits, and profitability of recent earnings play pivotal roles. Simultaneously, trade patterns driven by shipper demand, operational changes, and political influences also influence decision making. These determinants culminate in three potential outcomes for the ship: life extension through retrofitting, maintenance, and repair; scrapping the vessel; or resale on the secondhand market. This decision-making framework aligns with the discussion in Section 2.2.1, emphasizing the significance of sustainability and economic viability in ship-related decisions. The chart underscores the multifaceted considerations of ship owners, which could be further influenced by the dynamics of green ship recycling practices and their economic implications.

2.2.1 Factors Influencing Green Ship Recycling

The global shipping industry has recently responded to growing sustainability concerns regarding the sector performance. It promises to reduce global greenhouse gas emissions by 50% by 2050 (Milios et al., 2019). Hsuan and Parisi (2020) defined the green ship recycling as it is the “recycling that is compliant with regulations and international standards for health, safety, and environmental (HSE) management.” The "green" yards typically provide lower prices than other yards operating within the same region. This price difference primarily stems from the additional expenses associated with maintaining high health, safety, and environmental (HSE) standards as well as investments in recycling facilities and workforce welfare, which are prerequisites for conducting green ship recycling (Jain et al., 2017). The ‘green’ ship recycling yards are economically unattractive to most ship owners due to the comparatively lower prices offered for the same ship. To encourage environmentally friendly "green" ship recycling practices, these yards need to narrow or eliminate the existing price gap between "green" and "non-green" ship recycling options. They must either increase their revenue or lower the cost of recycling ships. It is important to narrow the price gap while maintaining stringent HSE standards, considering the upcoming international regulations on ship recycling, such as the Hong Kong Convention and EU Ship Recycling Regulation (Jain et al., 2017; Du et al., 2021). Determining the factors affecting green ship recycling is a vital process that ship recycling companies and policymakers can use to guide ship disassembly processes.

Figure 18 defines the interrelated components crucial for effective green ship recycling. Central to the diagram is the theme of "Green Ship Recycling," which intersects with five overarching domains: management, technological, environmental, resource consumption, and hazardous materials. Within the Management sphere, emphasis is placed on high information transparency, bolstered by a professional organization's oversight, and consistent resource monitoring. The Technological domain highlights the incorporation of high-level technology, anti-pollution facilities, and adherence to the established rules. From an environmental standpoint, monitoring systems and risk prevention are of paramount importance. Resource Consumption underscores the importance of clean energy utilization, minimal resource wastage, and limiting pollutant release. Finally, the Hazardous Materials sector emphasizes safe waste disposal. The Venn diagram's interconnectedness signifies the symbiotic relationship between these domains, reinforcing the necessity for a holistic approach in implementing green ship recycling. (Zhou, Du, et al., 2021).

2.2.1.1 Management Factor

Robust environmental regulations and standards significantly influence the recycling of ships. Organizational and management factors refer to an organization’s rules and regulations, on-site management, and audit procedures (Zhou et al. 2021). Green ship recycling focuses not only on environmental aspects, but also on worker safety and social welfare. Zhou, Liang, et al. (2021) stated different factors affecting the workers’ safety during the dismantling process such as: disposal of hazardous materials, operation’s safety, used equipment, dismantling operation management, and safety awareness. Proper training, personal protective equipment, and a safe working environment are essential considerations to ensure the well-being of workers involved in ship dismantling activities. Compliance with these regulations ensures proper management of hazardous materials, waste disposal, and worker safety (Gunbeyaz et al., 2023).

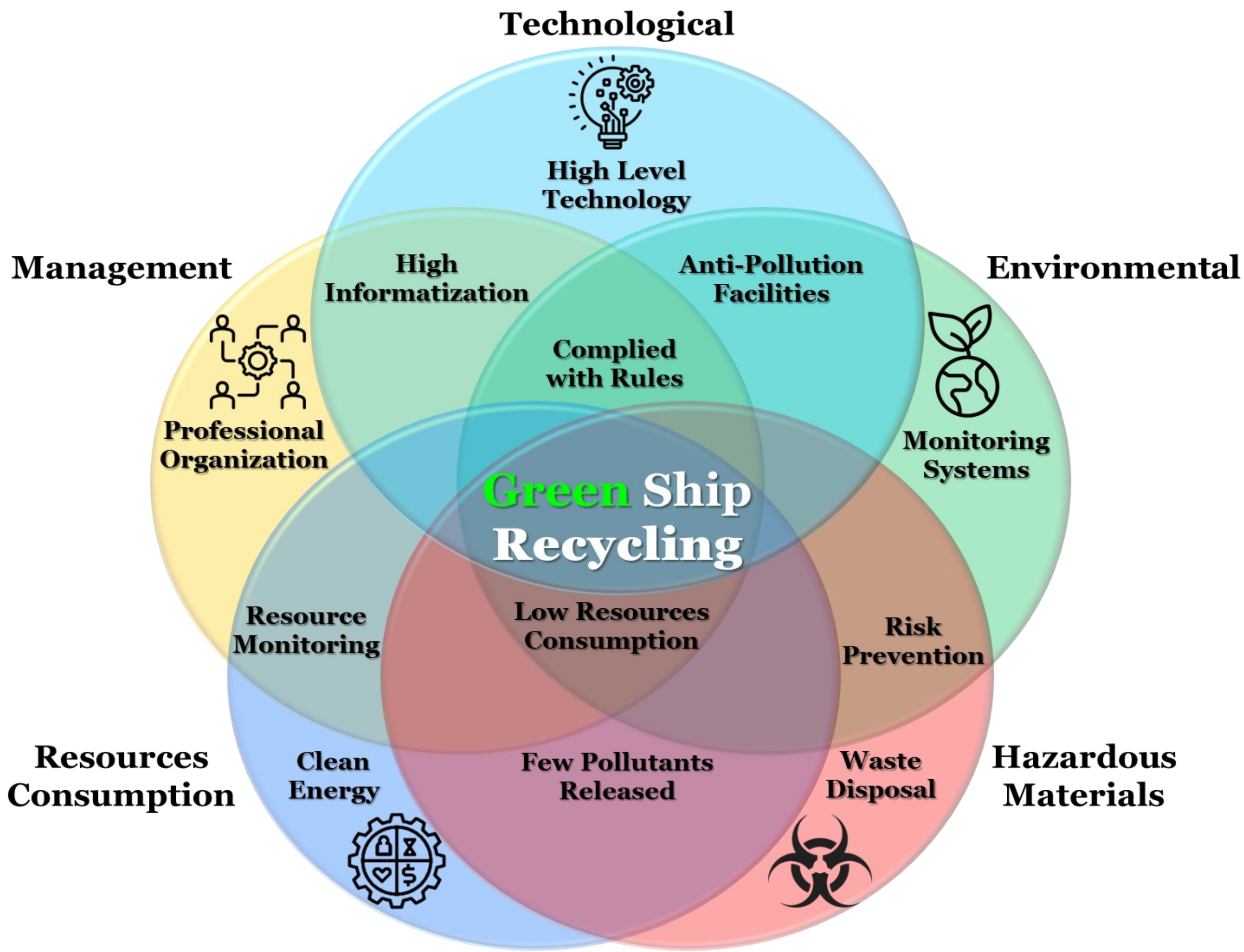


Figure 18. Green Ship Recycling Venn Diagram

2.2.1.2 Used Recycling Technology Factor

Ship recycling yards will experience an increase in operational expenses due to the implementation of new regulations that demand stricter standards for safeguarding the occupational health and environmental safety of workers engaged in recycling operations. To thrive in an industry dominated by low-cost substandard yards, it is necessary to enhance existing operational procedures and productivity levels. This improvement is necessary to remain competitive and to ensure sustainability in the market. To address the capacity issue, one solution is to enhance the efficiency and productivity of ship recycling facilities by optimizing the recycling processes (Jain et al., 2017). Optimizing these processes will not only reduce costs but also increase the output of shipyards, leading to higher earnings and ultimately expanding the capacity of yards in the long run. Advancements in ship recycling technologies also significantly impact the sustainability of the process. Innovative methods for ship dismantling, such as advanced cutting techniques, automated material separation, and on-site waste treatment, can enhance resource recovery and reduce environmental impact (Gunbeyaz et al., 2020). Jain et al. (2017) stated that implementing waste management strategies such as "waste-to-energy" can potentially generate an additional revenue stream for recycling yards that are willing to invest in advanced technologies capable of managing the diverse range of waste generated during ship recycling. One such technology is plasma gasification, which can convert waste into valuable products, such as vitrified glass, reusable metal, and synthetic gas. This synthetic gas can then be utilized for energy production through generators, gas turbines, and boilers. Thus, the adoption of environment-friendly technologies is vital for promoting green ship recycling.

2.2.1.3 Environmental Protection Plans Factor

The availability of appropriate infrastructure and facilities plays a vital role in green ship recycling. Ship recycling yards require well-equipped facilities for safe dismantling, material separation, waste management and recycling. An adequate infrastructure ensures that operations are conducted efficiently and comply with the environmental regulations. Recycling yards typically implement various precautions to ensure their safety and compliance. These measures include employing trained and qualified workers and utilizing specialized clothing and tools, such as disposable cloths, masks, grooves, and protective footwear with respiratory devices. Continuous monitoring of the work environment was conducted, including regular checks of the concentration levels. Additionally, workers who manage lead undergo annual occupational health assessments to safeguard their wellbeing (Du et al., 2018).

2.2.1.4 Resources Consumption Factor

Energy consumption is a significant factor that influences the sustainability and environmental impact of green ship recycling. The process of ship dismantling requires various energy-intensive activities such as cutting, lifting, and handling of ship components, as well as the processing and transportation of materials. The amount of energy consumed directly affects the overall carbon and environmental footprints of the recycling operation. Minimizing the energy consumption in green ship recycling is essential for reducing greenhouse gas emissions and promoting sustainable practices. Several strategies can be employed to optimize energy use during the recycling process, including efficient equipment and machinery, renewable energy sources, process optimization, and Energy Management Systems. Reducing energy consumption in green ship recycling not only lowers the environmental impact, but also contributes to cost savings and enhances the economic viability of recycling operations.

The concept of green ship recycling represents a shift towards sustainable and environmentally responsible practices in the disposal of EoL ships. Figure 18 shows the mutual activities among the five factors to achieve the concept of green ship recycling. It acknowledges the need to minimize the negative impact on the environment, enhance resource recovery, and prioritize the health and safety of workers involved in the recycling process. Green ship recycling embraces principles such as the reduction of hazardous substances, proper handling and disposal of waste materials, and promotion of recycling and reuse of ship components. Adhering to these principles, it aims to create a circular economy within the maritime industry in which materials from decommissioned vessels are recovered and reintegrated into new products or processes.

Figure 19 shows a comprehensive flow of the Green Ship Recycling Process, emphasizing the meticulous design of each stage to champion ecological and safety considerations. Commencing with preparatory measures such as writing a ship recycling plan and a detailed inspection report, the process highlights the industry's emphasis on planning and documentation. The infusion of safety protocols, represented by steps like 'Ship Anchoring to the Dock' and 'Fill Up Safety Forms and Set Up Safe Cautions,' signifies the industry's commitment to worker and environmental safety. Moreover, the sequence of dismantling from the superstructures to the bottom of the ship underscores a methodical approach aimed at maximizing material recovery and minimizing waste generation.

The depiction of waste generation at various intervals, such as during insulation removal or cable extraction, highlights the inherent challenges in the recycling process. These challenges necessitate advanced disposal and recycling strategies to preserve the 'green' ethos. Concluding with 'Site Clearance' and the 'Writing Ship Recycling Report' underlines the process's full circle, ensuring that every stage, from initiation to culmination, remains transparent, sustainable, and efficient. By focusing on the distinct dismantling phases and highlighting waste generation, this figure highlights the critical junctions where intervention can ensure eco-friendly recycling. Such a detailed roadmap not only enhances our understanding of green ship recycling but also serves as a beacon for industries aiming to embrace a sustainable future.

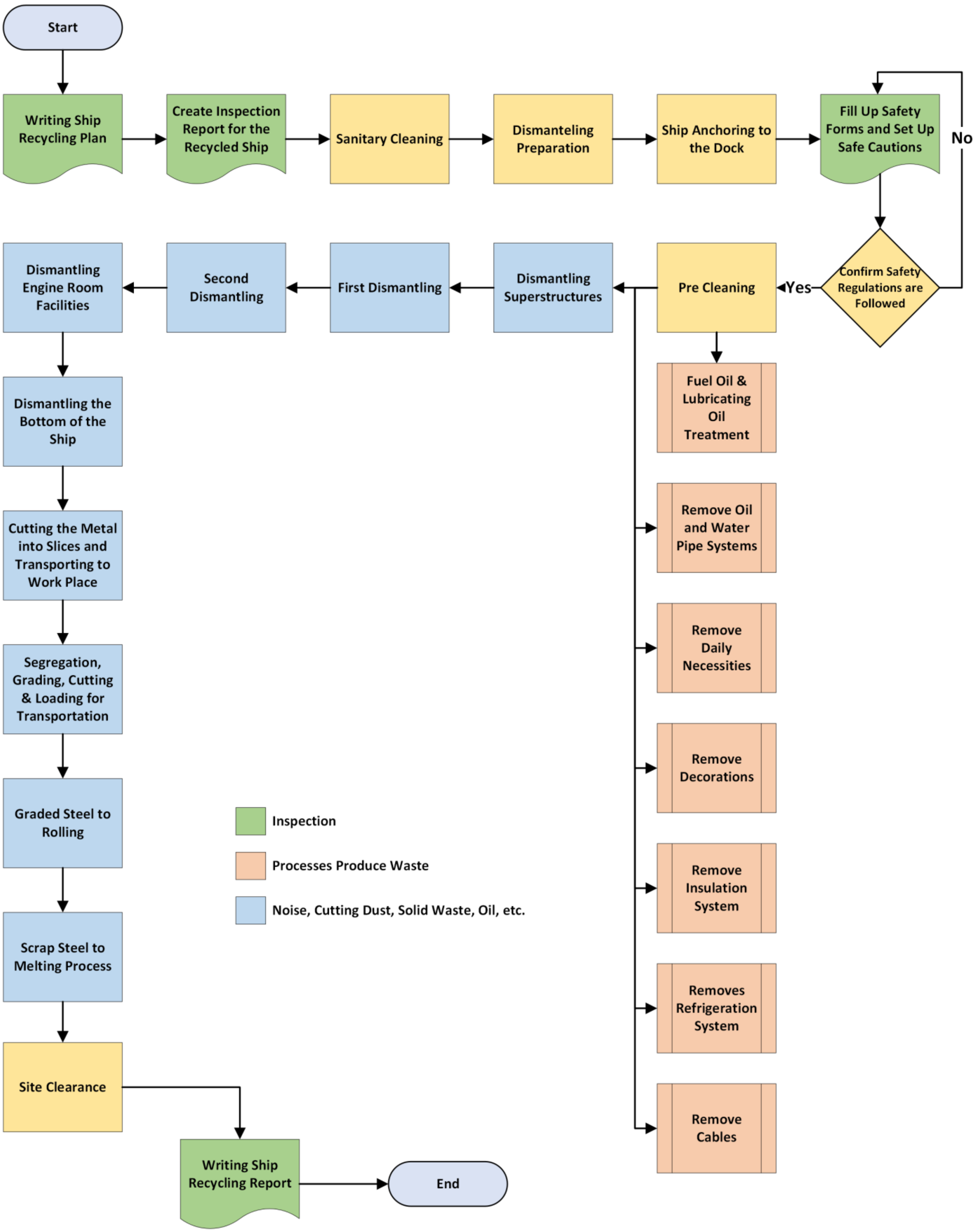


Figure 19. Green Ship Recycling Process Flow
Source: Based on (Zhou, Du, et al., 2021)

2.2.2 Sustainability Challenges

Currently, the world is moving towards sustainable development through the circular usage of limited planetary resources and resource recovery industries, such as recycling EoL ships, remanufacturing lithium-ion batteries, and reprocessing construction and demolition waste (Dey et al., 2021). The ship recycling industry is an integral part of the economies of developing nations because it is a significant source of local employment. The ship recycling sector faces several challenges, including environmental pollution, worker safety and health conditions, and weak legal systems (Du et al., 2017).

Figure 20. PEST Analysis for Ship Recycling Challenges

2.2.2.1 Political Challenges

Several political challenges have hindered effective implementation of sustainable ship recycling. These challenges arise from a combination of factors including the global nature of the industry, varying regulations across countries, economic interests, and geopolitical considerations. Ship recycling is a global industry and ships often change their ownership and cross multiple jurisdictions. Achieving international coordination and consensus on sustainable ship recycling practices and regulations is challenging because of differing priorities, national interests, and levels of economic development among countries. Even when international regulations exist, enforcing these regulations and ensuring compliance can be challenging. Political will and commitment are necessary to establish effective enforcement mechanisms, monitor compliance, and be accountable to those who violate sustainable ship-recycling practices. As previously mentioned, ship recycling is often concentrated in countries such as India, Bangladesh, and Pakistan. These countries may have different geopolitical dynamics including strategic interests, regional rivalries, and political alliances. Geopolitical considerations can influence the willingness of countries to adopt sustainable ship recycling practices (Dey et al., 2021).

2.2.2.2 Social Challenges

These challenges stem from issues such as occupational health and safety, labor rights, community well-being, and the overall social sustainability of the industry (Cairns, 2014). Ship dismantling can be hazardous due to the presence of heavy machinery, sharp metal parts, toxic substances, and unsafe working conditions (Gunbeyaz et al. 2023). Ensuring the occupational health and safety of workers is a significant social challenge that involves providing proper training and protective equipment and ensuring compliance with safety regulations. Moreover, ship dismantling yards are often located near residential areas, which can lead to social and environmental concerns in the local communities (Muhibbullah et al., 2014). These concerns include noise pollution, air and water pollution, community displacement, and impacts on livelihoods, creating a new topic of interest for the IMO fully dedicated to the pursuit of 'greening' maritime operations and putting an end to unsafe labor practices (Knapp et al., 2008). Skilled workers must be trained for safe and sustainable practices. Therefore, stakeholders are required to provide access to skill development programs for workers.

2.2.2.3 Economic Challenges

As mentioned before, scrap price is one of the factors that affects the decision to recycle ships. Thus, the economic dynamics of the ship recycling industry, financial considerations, and the costs associated with adopting sustainable practices are the main economic challenges. Applying sustainable ship recycling practices incurs higher costs than the conventional methods. Implementing technologies, ensuring compliance with regulations, providing adequate safety measures, and training require financial investment (Devault et al., 2016). Therefore, the challenge is to balance the economic viability of ship recycling operations with the additional cost of sustainability. Adhering to international regulations and standards for sustainable ship recycling can involve additional costs such as conducting environmental assessments, implementing pollution control measures, and ensuring worker safety. The economic burden of compliance can be challenging, particularly for yards operating in regions with limited resources and infrastructure (Dey et al. 2021).

2.2.2.4 Technological Challenges

In addition to the effect of economics, particularly the financial crisis, the ship dismantling market can be affected by other factors such as technical improvements in ships. These challenges arise primarily from the complex nature of ship recycling and the need for innovative technologies to improve safety, environmental performance, and resource recovery (Yin and Fan, 2018). Ship dismantling involves cutting and separating various components including steel, machinery, equipment, and hazardous materials. The development of safe and efficient technologies for dismantling large vessels, particularly those containing hazardous substances, is required. This industry requires a substantial energy input for cutting, crushing, and melting steel components. Therefore, one of the main technological challenges is to develop energy-efficient processes and technologies, as well as optimize resource recovery from ship components, such as metals and equipment (Tewari et al., 2001). However, ship recycling generates a significant amount of waste, including hazardous and nonhazardous materials. The development of advanced waste management technologies, including recycling and proper disposal methods, is necessary to minimize environmental impacts and promote resource efficiency (Dey et al., 2021). In addition, the introduction of automation and robotics into ship recycling processes can improve safety, productivity, and efficiency. However, adapting these technologies to the complex and variable nature of ship recycling poses challenges such as the handling of irregularly shaped components and hazardous materials.

The ship recycling industry faces significant challenges (summarized in Figure 20) in achieving sustainable practices, but there is growing awareness and commitment to addressing environmental and social concerns. Efforts from governments, industry players, and international organizations are shaping the future of ship recycling to establish transparent, safe, and environmentally friendly industries. By embracing technological advancements and adopting circular economy principles, the industry can enhance its contribution to the sustainable maritime sector by promoting resource conservation, environmental protection, and the well-being of workers involved in ship recycling activities.

2.3 Circular Economy and Ship Recycling

Recently, worldwide attention to CE has grown to overcome the current production and consumption model, which is based on continuous growth and increased resource throughput (Ren et al., 2023). This can be observed in the number of publications related to CE. According to SCOPUS records, the number of publications increased from 13 articles in 2012 to 227 articles in 2022. Ren et al. (2023) explained in their article the relationship between the CE and other keywords, the study was performed on 253 words. As shown in Figure 21, keywords were divided into six clusters. What we need to focus on here is the strong connection between CE and words such as recycling, bioeconomy, the general environment, and mechanical properties. In addition, "the blue clusters are centralized on sustainability, which relates to other keywords such as life-cycle assessments, reverse logistics, business models, and cleaner production. The yellow cluster is centralized on technological transfer, which is related to other keywords such as innovation, sustainable development, and performance (Ren et al., 2023). This shows a strong relationship between CE and the ship recycling industry. By encouraging the adoption of closed-loop production patterns within an economic system, CE aims to improve resource use efficiency by focusing on urban and industrial waste to achieve a better balance and harmony between the economy, environment, and society (Ghisellini et al., 2016). Dismantled ships contain large quantities of recyclable materials, such as liquids, tempered steels, copper, titanium alloys, aluminum, and electronic equipment. Approximately 85–95% of the materials in EoL ships have a high recovery value, which makes the ship recycling industry significant for CE (Steuer et al., 2021). Figure 21 was created using VOSviewer, which specializes in illustrating networks and bibliometric information, enabling the exploration of connections, simultaneous occurrences, and groupings among terms, authors, and documents (Yun and Ülkü, 2023).

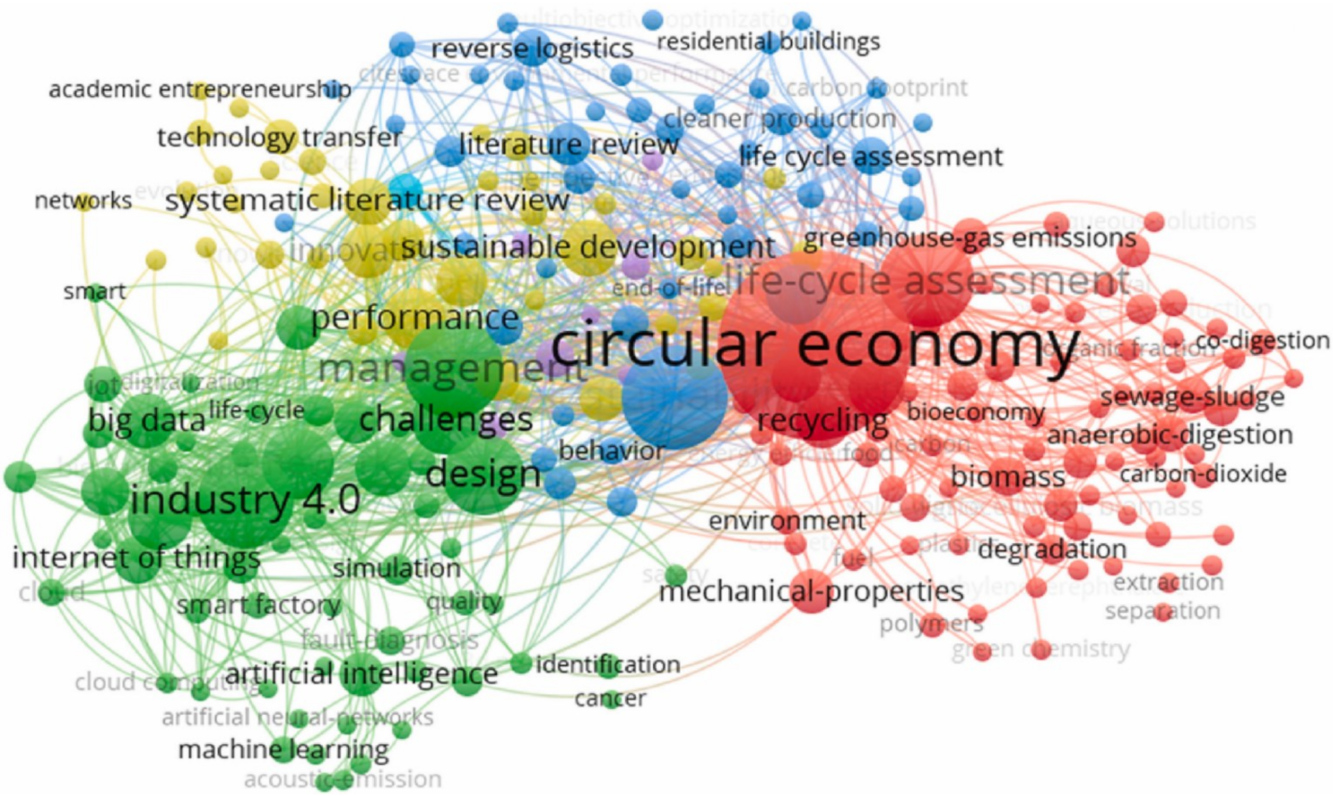


Figure 21. Cluster Network Shows Relationship Between CE and Other Keywords
Source: (Ren et al., 2023)

Three fields form the creation of a CE: ecological economics, environmental economics, and industrial ecology (Ghisellini et al., 2016). CE successfully combined several hypothetical areas to develop an alternative growth model for decoupling. For example, CE acknowledges entropic limits, indefinite metal recyclability, and the restoration of ecological provision/services to economic systems. From environmental economics, CE takes a holistic idea, system thinking, organizational learning, and human resources development, from industrial ecology, CE draws from understanding material and energy flows between industry and the environment (Rahman and Kim, 2020).

Rahman et al (2021) suggested that about 300 million gross tonnages will be available for demolition in the next five years and the inability to get them recycled would cost about 20 billion dollars. It also provides direct and indirect employment for over 100,000 workers in Bangladesh and India (Rahman and Mayer, 2015). More importantly, South Asian recycling nations have suffered from economic losses and employment opportunities. In addition, among the four recycling methods mentioned earlier, the beaching method stands out for its lack of pollutant containment, which demands special attention to the management of hazardous materials, such as asbestos, protection of the environment, and safety of workers (Zhou, Du, et al., 2021). Considering these challenges, it is unsurprising that most ship recycling activities occur in regions of the global south, where regulatory standards and labor remuneration are low (Alam and Farooque, 2014; Choi et al., 2016; Hiremath et al., 2016).

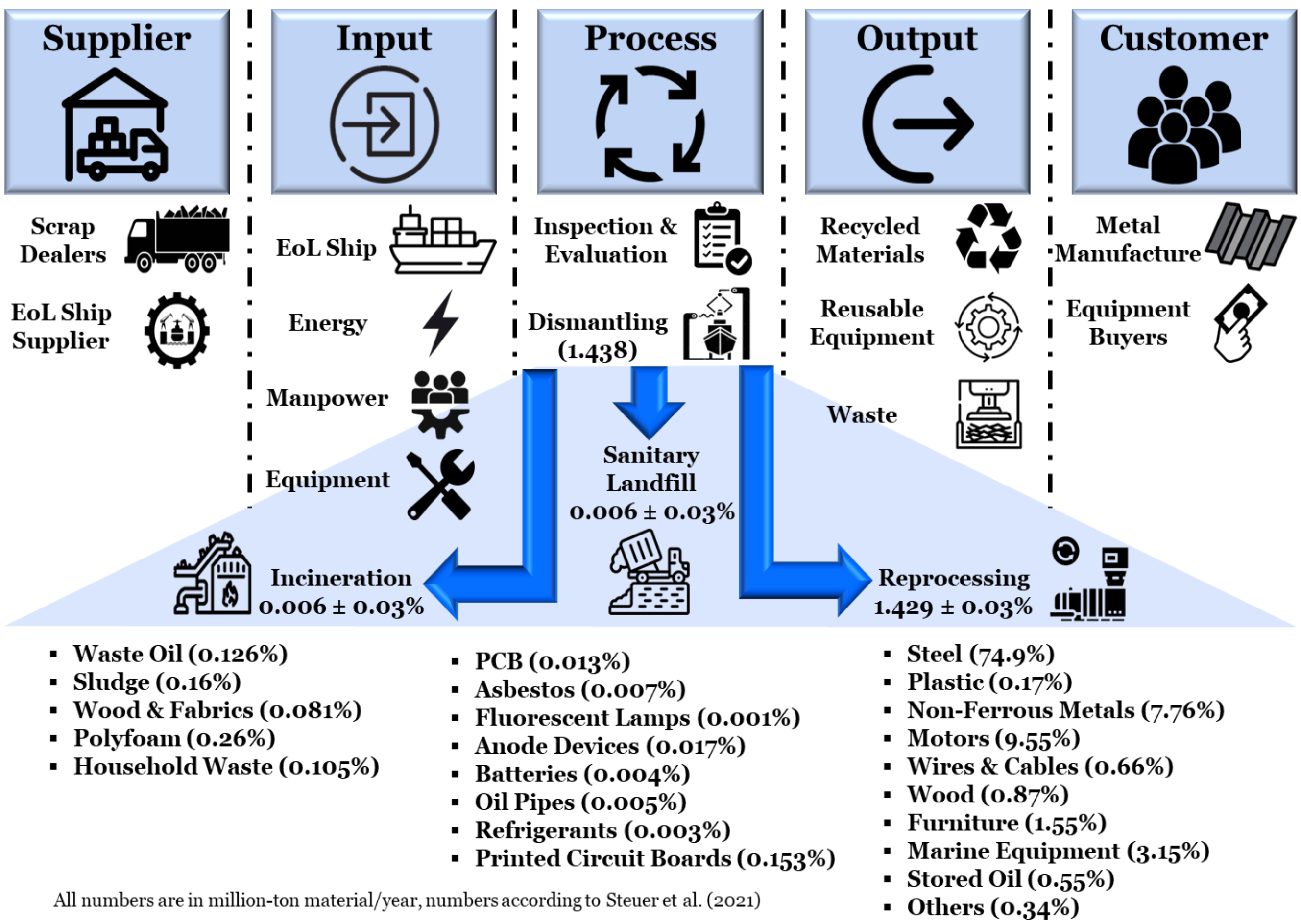


Figure 22. Ship Recycling SIPOC Diagram

Steuer et al. (2021) indicated in their study that 99% of the dismantled ship materials can be recovered. Where hazardous materials form approximately 1%, these numbers are relatively higher than the findings in other papers, and differences in waste categorization play a significant role. Upon delving into specific fractions, the above SIPOC diagram (Figure 22) shows that scrap steel constitutes approximately 75% of recyclable secondary resources, whereas non-ferrous metals constitute 7.8%. Ship motors constitute a substantial fraction (9.6%), offering the potential for refurbishment, reuse, or scrapping valuable content. Approximately 6, 500 tons (0.4%) of the remaining hazardous fractions (average 0.65%) were subjected to incineration, whereas the remaining 2,900 tons (0.2%) were transferred to landfills. From an environmental and sustainable development perspective, the circular economy model is rarely applied in developing countries compared to developed nations. Korhonen et al. (2018) defined the CE as follows: "Circular economy is an economy constructed from societal production-consumption systems that maximize the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical material flows, renewable energy sources, and cascading type energy flows" (Figure 23). CE is based on a fragmented collection of ideas from scientific fields, including emerging and semi-scientific concepts. For example, these sources include industrial ecology, cleaner production, industrial symbioses, industrial ecosystems, zero-emissions concepts, and product service systems.

Currently, the worldwide system follows a linear economy, mainly taking, making, and disposing of the models. However, we have a circular economy model that involves the production, consumption, and disposal of waste to recycle it for further production. Therefore, it is mainly managed using the 3R concept. Therefore, the CE model is one of the most environmentally friendly and sustainable development approaches (Ahmed et al., 2022).

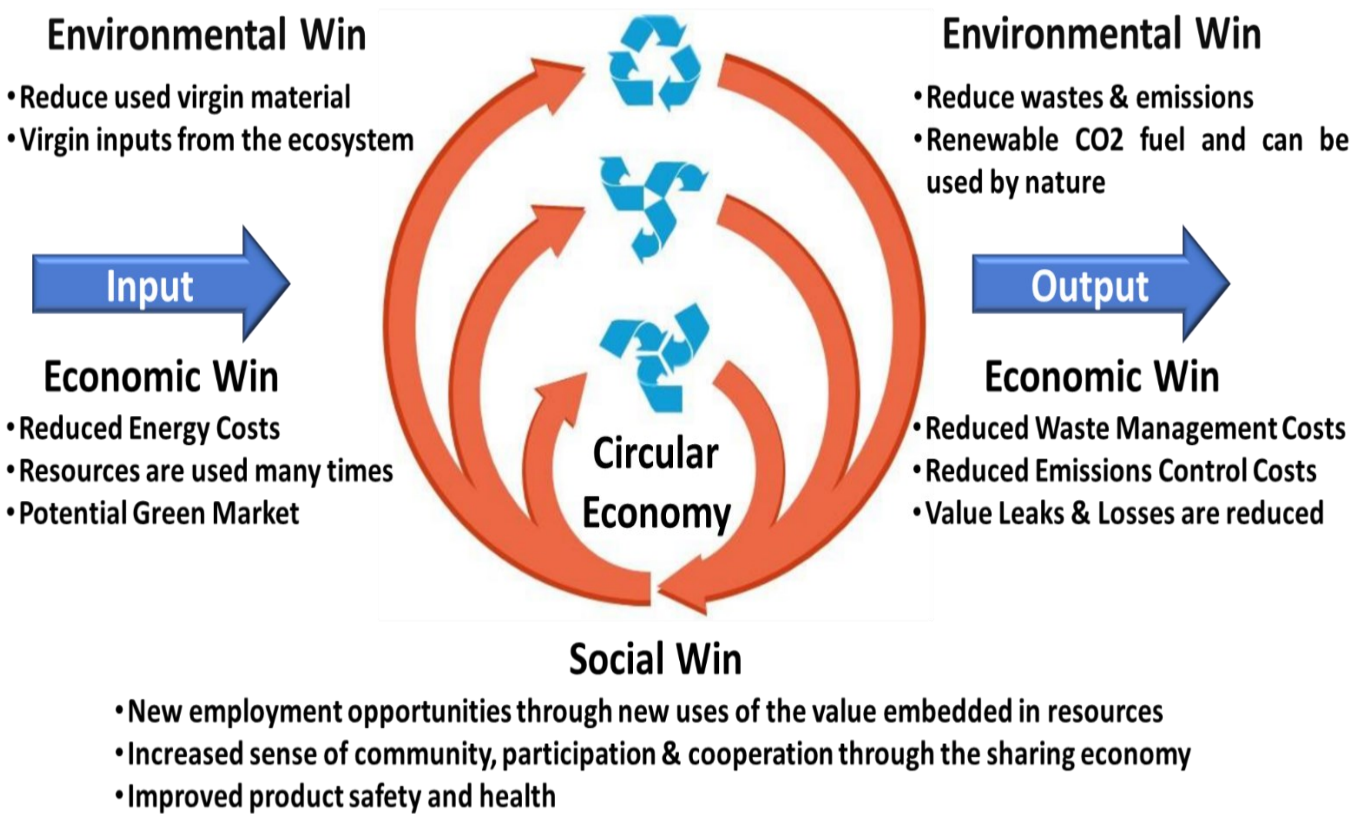


Figure 23. The Win-Win Situation of Circular Economy

2.3.1 Transformation from LE to CE

The linear model, also known as the 'take-make-dispose' model, depends on large quantities of easily accessible resources and energy and, as such, is increasingly inadequate for the reality in which it operates. de Oliveira et al. (2021) explained the process as follows: “This process begins with "take," the extraction of natural resources, followed by "make," the production of goods and services, and "distribution," when the product is delivered to the consumer.” Working towards efficiency alone will not change the finite nature of stocks, but can only delay the expected. Transitioning to CE requires supporting conditions that remove obstacles during product life extension and material recovery operations. CE refers to an industrial economy that is healing by intention, aims to depend on renewable energy, minimize, track, and eliminate the use of toxic chemicals, and eliminates waste through cautious design. The term extends beyond the mechanics of the production and consumption of goods and services in the areas it seeks to redefine. The concept of CE is grounded in the study of non-linear systems, mainly living systems. The main consequence of taking insights from living systems is optimizing systems rather than components, which can also be referred to as “design to fit” (EMF, 2015).

Consequently, a circular economy forms a sharp difference between the consumption and use of materials. A circular economy advocates the need for a “functional service” model in which manufacturers or retailers increasingly retain ownership of their products and, where possible, act as service providers, selling the use of products, not their one-way consumption. This shift has direct implications for developing efficient and effective take-back systems and the proliferation of product and business model design practices that generate more durable products, facilitate disassembly and refurbishment, and consider product-service shifts where appropriate (EMF, 2015). In line with Figure 19, Ülkü et al. (2022) explained the salient features of a CSC compared to its linear (traditional) and sustainable counterparts as follows: “The CSC is a sustainable and resilient supply chain designed to end waste by valorizing any material flows in shortened loops and slowing down consumption. Within a circular economy, which requires systems thinking and compliance with Quadruple Bottom-Line (QBL) imperatives (cultural, economic, environmental, and societal long-term well-being), as shown in Figure 25, a CSC creates restorative and regenerative products and processes, while co-creating with stakeholders (across multiple industries, public sectors, and consumer markets) a shared value via the circulation of resources (raw materials, by-products, end-of-life and end-of-use products, disposal of waste, process capabilities), and timely and transparent information”.

As illustrated in Figure 24, CSC incorporates both an open loop and a closed loop. The materials (i.e., raw materials, by-products, or EoL products) and process capabilities (such as idle manufacturing capacity) that are recovered during the primary stages of an SC (sourcing, manufacturing, and delivery) are reintroduced into the system as “circular resource flows.” These circular resource flows can be restored within the closed-loop end of the CSC through activities such as reusing, refurbishing, remanufacturing, repurposing, and recycling components. These resources can be utilized within the same industry or in other industries as inputs in the open loop. Any biological waste that remains, which would otherwise have been disposed in landfills, is regenerated, and transformed into biological nutrients. These nutrients are returned to the biosphere and serve as natural capital for future reuse (Ülkü et al. 2022).

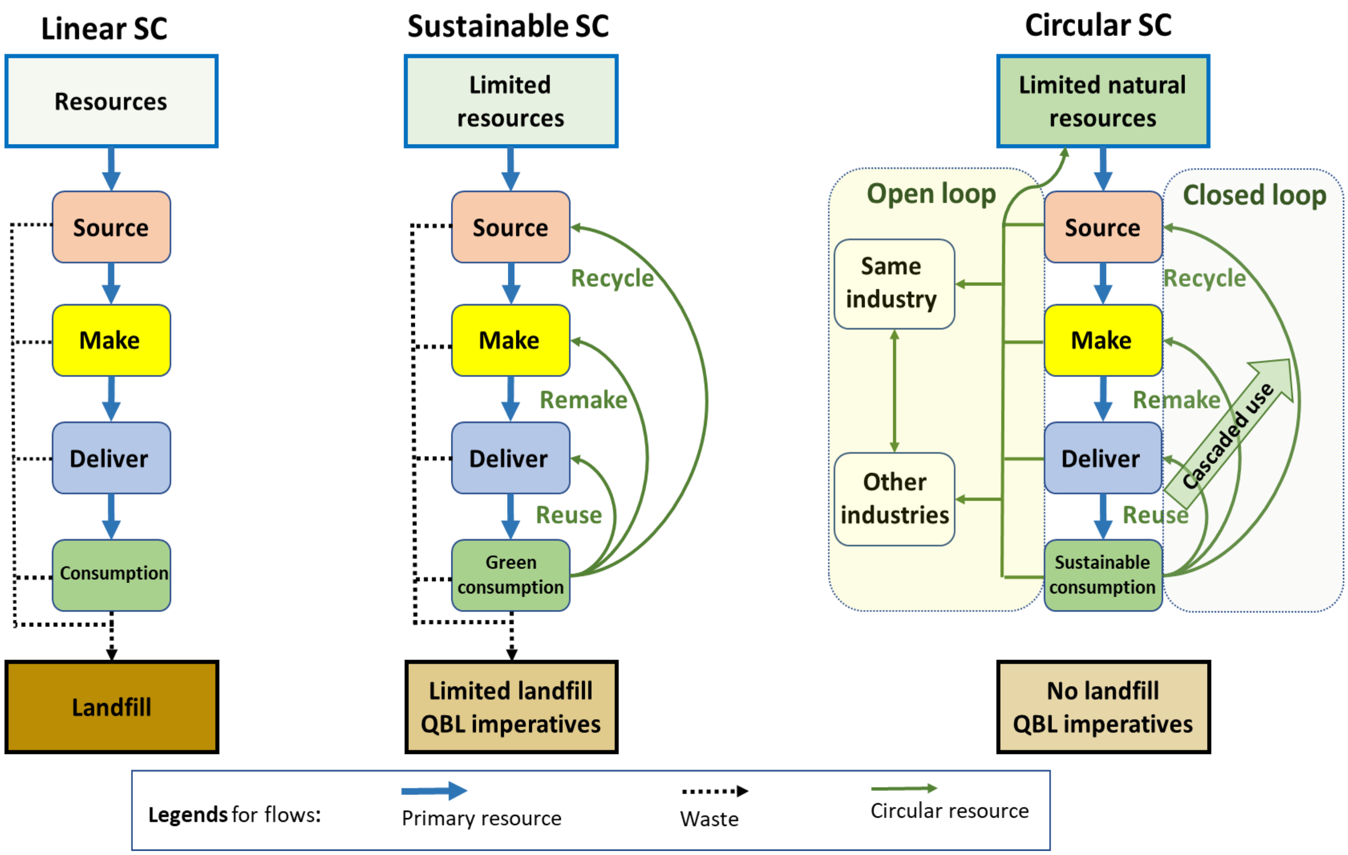


Figure 24. LE Vs. Sustainable SC Vs. Circular SC
Source: (Ülkü et al., 2022)

The transformation from LE to CE in the ship recycling industry holds tremendous potential for sustainable and responsible practices. By shifting from the traditional "take-make-dispose" approach to one that prioritizes resource efficiency, waste reduction, and value retention, the industry can significantly reduce its environmental footprint. By embracing concepts such as designing for durability and recyclability, maximizing material recovery, promoting responsible disposal, and developing robust recycling infrastructure, the ship dismantling industry can achieve more sustainable and efficient operation. However, this transformation requires collaboration among stakeholders, supportive policies and regulations, and investments in research and innovation. With collective efforts, the ship recycling industry can transition towards a circular economy model, contributing to the conservation of resources, reduction of waste, and creation of a more sustainable maritime sector for future generations.

Figure 25. QBL Sustainability Pillars
Source: (Yun & Ülkü, 2023)

2.3.2 CE Limitations

CE has emerged as a compelling alternative to the linear model of resource consumption and disposal, offering a promising pathway for sustainable development. The circular economy emphasizes the principles of reducing waste, maximizing resource efficiency, and promoting regenerative economic practices. While the circular economy has garnered substantial attention and support from academia, policymakers, and industry leaders, it is imperative to critically assess its limitations to ensure its effective implementation. Korhonen et al. (2018) stated there are six limitations for CE: thermodynamic limits, system boundary limits, economy's physical scale, path-dependency and lock-in limits, social and cultural definitions, and limits of governance and management. This section briefly identifies the six limitations in terms of environmental sustainability.

2.3.2.1 Thermodynamic Limits

The fundamental principles of thermodynamics suggest that within the circular economy framework, priority should be given to product reuse, remanufacturing, and refurbishment over recycling for raw material value or combustion for energy. Recycling and combustion are less preferable options, and should be avoided whenever possible. It is crucial to maximize the lifespan and utilization of products before considering recycling or energy recovery. Landfilling is the least desirable option. However, it is important to note that all these processes are governed by the laws of physics. Therefore, it is theoretically possible to achieve complete recycling with the aid of sun-derived renewable energy. However, this would necessitate significant efforts in terms of locating, retrieving, and processing dissipated materials and nutrients. Nevertheless, within the current global linear throughput production-consumption market economy, significant progress can be achieved by redirecting physical flows towards a more cyclical model.

Thus, embracing cyclical material flows and renewable energy cascades presents a vital opportunity to establish a more sustainable model for global material and energy flow. However, even in the context of entropy, it is important to subject every circular economy endeavor or process to a thorough analysis to evaluate its net environmental sustainability contribution. Mere circularity does not guarantee sustainable outcomes. For instance, the utilization of forest residues for renewable energy and as a substitute for fossil fuel combustion may involve the removal of nutrient-rich components such as twists, needles, bark, and branches from the forest ecosystem, which play a crucial role in supporting ecosystem health, biodiversity, and forest growth (Korhonen et al., 2001). This activity requires energy and machines that depend on the energy required for operation. Furthermore, the manufacturing processes of these machines require energy and materials to generate waste and byproducts. Therefore, the sustainability impact of circular economy projects requires meticulous case-by-case analysis (Korhonen et al., 2018).

2.3.2.2 Spatial and Temporal System Boundary

In terms of the physical flow of materials and energy, the current global economic system is primarily a linear throughput flow economy. Almost 75% of the global energy production is based on non-renewable and emission-intensive fossil fuels, the combustion of which does not adapt to the biosphere's reproductive cycles. Dead resources are extracted from nature, from the lithosphere, processed, used, and dumped back to living nature into the biosphere in a harmful form. Therefore, although sustainable development is a global goal, CE-type projects that have been implemented and that will be implemented soon will always be local or regional at most. There is no global body of governance. However, perhaps gradually and step-by-step from the roots up the world of the future could be transformed towards something like the CE vision, provided the vision is clear enough and in line with sustainability (Korhonen et al., 2018). It is possible to identify the key issues and challenges in the CE approach to global net sustainability. One such issue is the delineation of spatial system boundaries. As the physical flows of materials and energy traverse organizational, administrative, and geographical boundaries, the phenomena of problem displacement and problem shifting come into play. It is essential to minimize these phenomena, which involve reducing the environmental impact in one part of the system by transferring the problem to another part of the system. Numerous instances exist in which efficiency gains, environmental improvements, and social benefits achieved in local and regional economies have resulted in difficult problems surfacing elsewhere, either directly or indirectly, through supply chains, value chains, product life cycles, and associated networks (Korhonen et al., 2018).

2.3.2.3 Economy's Physical Scale

The physical scale of the economy can limit the implementation of the CE concept. It relies on the efficient use of resources and continuous circulation of materials within the economic system. However, the sheer size and magnitude of the economy can create challenges in achieving this goal. Korhonen et al, (2018) stated that the physical scale of the economy is different from the size of the economy measured in abstract exchange value. By utilizing commonly available statistics and general knowledge, it is evident that the physical scale of the global economy, as measured by its material and energy flow footprint or overall natural resource utilization, is projected to continue growing over the next 50 years. This growth is expected to persist even though the CE concept is currently operating relatively well in industrialized Western nations. However, it should be noted that the circular economy in these countries is still in the early stages of development. The combination of population growth, rising living standards, and urbanization in developing and transitioning economies is anticipated to outweigh the potential gains in global net sustainability contributions that can be achieved through CE innovations in developed countries.

2.3.2.4 Path Dependency and Lock-In

Once economic innovation enters the market, the process unfolds to determine its impact and influence. Typically, the initial idea of gaining acceptance enjoys the greatest market share and attracts the most attention. Factors such as returns to scale and learning effects further strengthen the position of the first innovation in the market, making it more dominant than the subsequent entrants. This phenomenon is commonly referred to as path dependency and lock-in (Norton et al., 1998) where the "survival of the first" takes precedence over the survival of the fittest. In the CE concept, path dependency means that the current LE model is deeply ingrained in existing infrastructure, supply chains, and consumer behavior. Industries and businesses have built on this linear system, creating inertia and resistance to change. However, lock-in arises from substantial investments in the current LE. Transitioning to a circular economy often requires significant investments in new technologies, business models, and infrastructure. Existing LE has attracted significant capital, making it difficult to redirect investments in circular practices. This lock-in effect can impede the adoption of CE principles, particularly in industries that rely heavily on a linear approach.

CE innovations that focus on physical material flow such as product reuse, remanufacturing, and refurbishment introduce complex issues in terms of path dependency. This issue arises because many firms rely on the availability of waste materials that can be utilized either as raw materials or as sources of energy. These waste-derived resources could serve as substitutes for virgin and fossil fuels. However, in CE, the availability of such waste flows may decrease when product lifespans are extended through high-value reuse, remanufacturing, and refurbishment. Consequently, firms that rely on these waste materials are compelled to increase their use of virgin resources and resort to fossil-fuel combustion. This scenario could potentially create an undesirable dependency on sustainability, specifically leading to an overall increase in the consumption of virgin resources. It is important to analyze which specific segments of the product/service supply chain, value chain, or life cycle are affected by this shift, and how they are impacted (Korhonen et al., 2018).

2.3.2.5 Social and Cultural Definitions

Factors such as history, culture, community, and society influence the determination of what constitutes a good or bad material flow. This definition is dynamic and subject to changes over time. They play a vital role in shaping governance, policy, and strategic management. However, the current statistics used by environmental administrations globally often overlook the material flow categories associated with CE. Existing statistics primarily focus on conventional waste material utilization through recycling and energy recovery, as categorized by the national environmental administrations in Western industrialized countries. By contrast, categories pertaining to product reuse, remanufacturing, and refurbishment are not clearly defined in these statistics. Consequently, the lack of official categorization makes it challenging to define and implement policies, legislation, or other public policy instruments specifically tailored for CE activities (Korhonen et al., 2018).

Moreover, the understanding of waste is fluid and thus subject to change. It is intertwined with cultural norms, societal values, community perspectives, historical contexts, and level of societal development. Identifying the exact moment at which materials transition from economic value to waste with little or no value is challenging. The perception of waste as a valuable resource for materials or energy adds complexity to the flow dynamics (Korhonen et al., 2018). In addition, distinguishing between waste and byproducts is difficult. When incorporating circular economy categories of product reuse, remanufacturing, and refurbishment, the traditional definition of material flow becomes highly problematic. Without a clear definition of the specific types or stages of physical material flow within economic systems, supporting their intentional utilization becomes exceptionally challenging. Furthermore, assessing the true environmental impacts of circular economy activities becomes arduous without a well-defined understanding of the types of materials and energy that are beneficial or detrimental from a sustainability perspective. Material flow is influenced by factors such as time, space, and culture. Consequently, it is imperative to situate all circular economy proposals and suggestions within their respective temporal, spatial, and cultural context. It is crucial to recognize that all definitions are rooted in culture, society, and community as they are social and cultural constructs.

2.3.2.6 Governance and Management Limits

Although change is a permanent aspect of economic development, most past changes were primarily aimed at improving existing production and consumption concepts rather than radically redesigning them (Mauss et al., 2023). However, CE "must be understood as a fundamental systemic change instead of a bit of twisting the status quo" (Kirchherr et al., 2017). Transitioning an organization's business model from a linear to a circular approach requires comprehensive and refreshed comprehension of value creation, delivery, and capture. To cultivate this renewed systemic mindset, internal organizational development is necessary, which is typically facilitated through change management processes (Lieder and Rashid, 2016). The scope of change management typically focuses on internal aspects within an organization. However, when transitioning to a circular economy, enhancing integration within the value chain is crucial. Consequently, internal advancements alone are insufficient without corresponding changes outside the organization's boundaries and vice versa. Achieving a successful transformation into a circular economy necessitates embedding corporate changes in a broader business environment.

However, shaping market conditions conducive to circular economy practices in industries, society, and politics largely falls outside the direct influence of individual companies, and is not typically addressed within the realm of change management (Mauss et al., 2023). The physical flows of materials and energy derived from nature within the economic production-consumption system encompass various interconnected components. Eventually, these flows are transformed into waste and emissions, which impact the ecosystem. It is important to note that these flows are not confined by artificial administrative, geographic, sectoral, or organizational borders. New business models have been proposed to embrace CE principles. These models encompass product designs that consider multiple life cycles, leasing, renting with retained ownership, and implementing reverse logistics in the supply chain. Inter-organizational sustainability management is essential for effectively implementing these models. This necessitates cooperation between supplier and customer firms (business-to-business marketing) as well as between producers and consumers, particularly in cases involving leasing or renting arrangements while retaining ownership of the product (Korhonen et al., 2018). These limitations require concerted efforts from stakeholders including governments, shipowners, shipbreakers, and regulatory bodies. This necessitates investment in the infrastructure. Technology, capacity building, harmonization of regulations, and establishment of transparent reporting mechanisms. Collaboration and knowledge sharing among stakeholders are crucial for overcoming these limitations and advancing the adoption of circular economy principles in the ship-recycling industry.

2.3.3 Why Go Circular?

According to the circularity gap report issued by the PACE organization (Circular Economy, 2022), they indicated that "the global economy is consuming 70% more virgin materials than the world can safely replenish: annual resource use was 89.8 billion tons in 2016 but passed 100 billion in 2019 and is estimated at 101.4 billion last year. More than 90% of what we take from the Earth to fulfil our needs and wants goes to waste, with only 8.6% of materials cycled". CE is a broad concept; however, three principles can be defined. The first involves preserving and enhancing natural capital by effectively managing finite stocks and maintaining a balance in the utilization of renewable resources. The second principle focuses on optimizing resource utilization by promoting the circulation of products, components, and materials at their highest levels of utility, encompassing both technical and biological aspects. The third principle aims to enhance the efficiency of the system by identifying and eliminating negative externalities from the outset, thereby ensuring greater sustainability (de Oliveira and Oliveira, 2023).

EMF (2015) highlighted five simple principles for CE. First and second, "design out waste" and "Waste is food" the objective is to maximize the utilization of materials and maintain their highest value for as long as possible by leveraging both technical and biological cycles. In addition, the core concept revolves around the reintroduction of products and materials into the biosphere through non-toxic restorative loops, which form the essence of biological nutrients. Similarly, on the technical nutrient side, there is potential for enhancing quality, a process known as upcycling. Third, "build resilience through diversity" systems that exhibit diversity, encompassing numerous connections and scales, tend to display greater resilience when confronted with external shocks compared to systems designed solely for efficiency. Fourth, "rely on energy from renewable sources," the objective is to preserve and enhance natural capital by relying on the utilization of renewable resources. Fifth, "Think in systems" ability to understand how parts influence one another within a whole and the relationship between the whole and parts is important. It considers elements related to infrastructure, the environment, and social contexts. Although machines are also regarded as systems, they are typically considered to be bound and deterministic. “Systems thinking usually refers to non-linear systems (feedback-rich systems).” CE is often associated with the concept of “Recycle,” but the most effective approach to achieving material efficiency and reaping economic and environmental benefits is to prioritize waste “Reduction” and “Reuse” (Rahla et al., 2021). The 3Rs approach was recently expanded to include more actions in the transition from LE to CE.

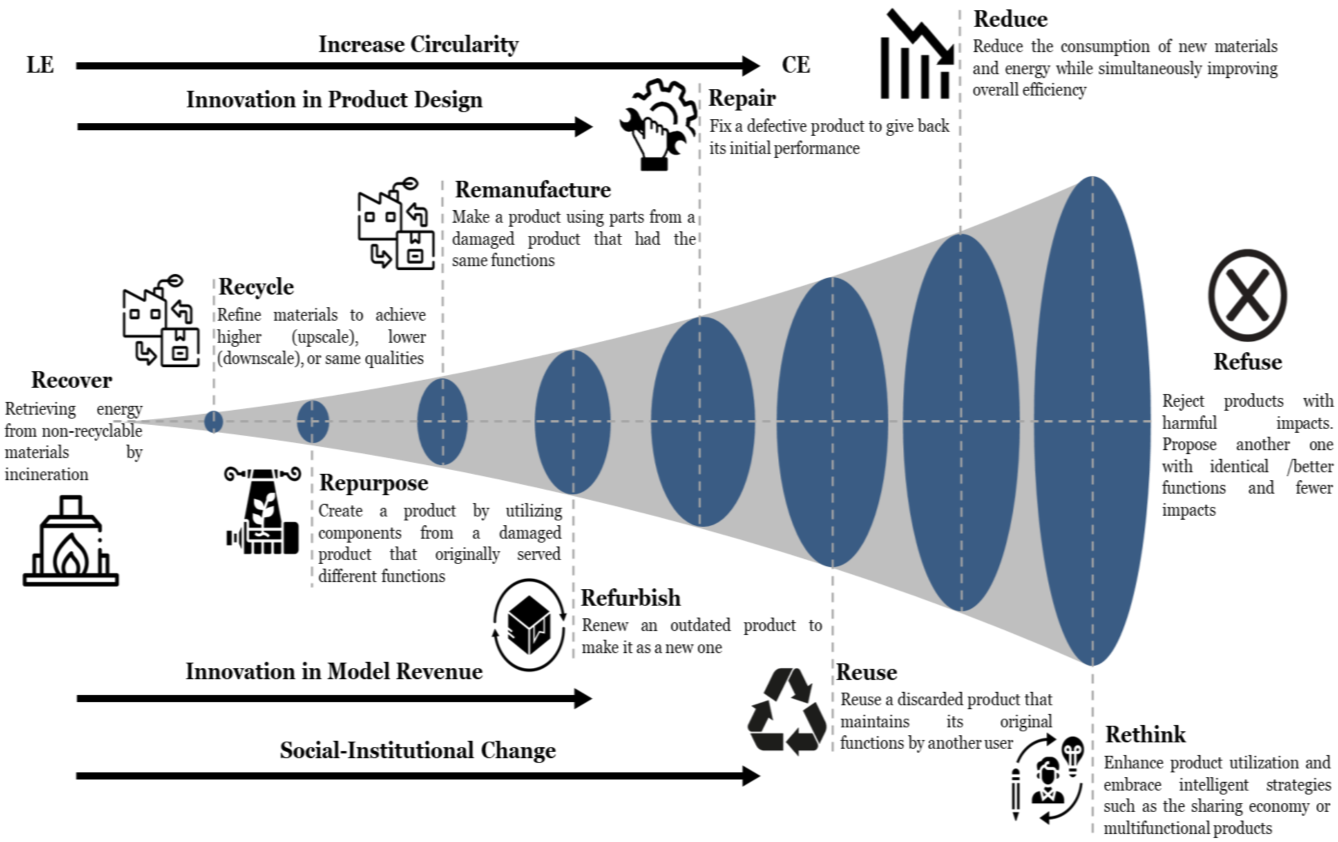


Figure 26. R-List Strategies to Transform from LE to CE
Source: Based on (Potting et al., 2017)

The “R-list” (Figure 26) shows the circularity principles required to transform from LE to CE. These strategies can be used in the ship-recycling industry. **Design Out Waste:** This principle is directly connected to the strategies of 'Reduce', 'Refuse', and 'Rethink' on the R-List. These strategies emphasize reducing the consumption of new materials and energy, refusing products with harmful impacts, and rethinking product utilization to minimize waste generation during the design phase. **Waste is Food:** 'Recycle', 'Remanufacture', and 'Repurpose' strategies embody the idea that waste should be converted into a resource. Recycling refines materials for reuse, remanufacturing uses parts from damaged products to create the same function, and repurposing creates new products from the old, aligning with the concept of converting waste back into useful inputs.

Build Resilience Through Diversity: 'Repair' and 'Refurbish' contribute to this principle by promoting the repair of defective products and renewing outdated products, respectively. These actions lead to a more diverse and resilient system in which products and components are maintained and used for longer periods, rather than being replaced. **Relying on Energy from Renewable Sources:** While explicitly listed in the R-List, the principle can be seen as an underlying theme across all strategies, as a circular economy encourages the use of renewable energy in all stages of the product lifecycle to minimize environmental impact. **Think in Systems:** The R-List itself is an outcome of systems thinking, in which the entire lifecycle of products is considered. The strategies of 'Reuse' and 'Recover' involve using a discarded product for its original functions by another user and retrieving energy from non-recyclable materials, respectively. Both strategies require understanding and designing complex systems in which materials and products flow in a loop while maintaining their value and utility within the system.

There are various strategies within the concept of circularity that aim to reduce the consumption of natural resources, minimize waste production, and prioritize sustainability. These strategies can be categorized based on their level of circularity, with some being more circular than the others. For instance, smarter product manufacturing and utilization, such as product sharing, are generally considered higher-priority strategies as they maximize the circularity of products by serving the same function or accommodating more users. The next option is to extend the lifetime of the products, followed by recycling of the materials through recovery. Incineration, which involves energy recovery but limits material reuse, is considered a lower-priority strategy in a circular economy. In general, higher levels of circularity correspond to greater environmental benefits (Potting et al. 2017). The circular economy concept in ship recycling not only offers environmental benefits but also presents economic opportunities. It can create new markets for recycled materials, stimulate job growth, and enhance the overall competitiveness of the ship recycling industry. By implementing circular economy principles, the ship recycling industry can contribute to a more sustainable and efficient use of resources, reduce environmental impacts, and support the transition towards a more circular and sustainable economy.

2.3.4 MCDM in Ship Recycling

Multiple-Criteria Decision-Making (MCDM) stands at the forefront of advancing sustainable practices within the ship recycling industry, an essential component of the circular economy. As the sector grapples with the complexities of balancing environmental integrity, economic feasibility, and social responsibility, MCDM provides a structured framework to navigate the intricate web of trade-offs and synergies inherent in this field. The integration of MCDM into ship recycling initiatives facilitates the transition from traditional linear models to circular approaches that emphasize resource recovery, waste minimization, and the lifecycle extension of materials. This paradigm shift, propelled by MCDM methodologies, enables stakeholders to make informed decisions that reflect the multifaceted goals of sustainability. By doing so, the ship recycling industry can align its operations with the circular economy's principles, ensuring that EoL vessels contribute to a regenerative economic system while adhering to stringent environmental and social standards. MCDM is concerned with making choices (like assessing, ranking, choosing, etc.) among different options which are typically defined by several, often opposing, criteria. Essentially, a problem of MCDM is structured into a hierarchy that includes four levels: the overarching aim, the objectives that support this aim, the criteria that define these objectives, and the various options available.

Table 7. MCDM Approaches in Ship Recycling Industry

Study	MCDM Approach								Sustainability Dimension			Targeted Stakeholder
	BWM	AHP	ISM	DEMATEL	VIKOR	TOPSIS	SWARA	TISM	Env	Eco	Soc	
(J. John & Kumar, 2016)		✓							✓	✓		Ship Owner
(Ozturkoglu et al., 2019)				✓					✓	✓	✓	Policymakers
(Akcan & Taş, 2019)						✓	✓		✓		✓	Shipyard
(Keyghobadi et al., 2020)							✓		✓	✓	✓	Policymakers
(Soner et al., 2021)	✓								✓			Policymakers
(Vakili et al., 2021)		✓				✓			✓	✓		Shipyard
(Caner & Aydin, 2021)		✓							✓	✓		Ship Owner
(Mannan et al., 2022)			✓						✓	✓		Policymakers
(Ozturkoglu et al., 2022)								✓	✓	✓	✓	Policymakers
(Mentes, 2023)					✓					✓	✓	Ship Owner
(Garg et al., 2023)		✓							✓	✓		Policymakers

Table 7 categorizes a broad array of techniques that have been applied to the strategic decision-making process in the ship recycling industry. These techniques include the Best Worst Method **(BWM)**, which streamlines the weighting of criteria through pairwise comparisons (Soner et al., 2021); Analytic Hierarchy Process **(AHP)**, which organizes complex decisions into a hierarchical structure for detailed analysis (Garg et al., 2023); and Interpretive Structural Modeling **(ISM)**, which maps out the interconnections between various elements defining a problem (Mannan et al., 2022). Additional methodologies such as Decision-Making Trial and Evaluation Laboratory **(DEMATEL)** visually model complex causal relationships, while multi-criteria optimization and compromise solution VlseKriterijumska Optimizacija I Kompromisno Resenje **(VIKOR)** identifies the best compromise among alternatives (Ozturkoglu et al., 2019). Technique for Order Preference by Similarity to Ideal Solution **(TOPSIS)** ranks alternatives based on their proximity to an ideal solution, and Stepwise Weight Assessment Ratio Analysis **(SWARA)** determines criteria weights in subjective judgment contexts (Akcan & Taş, 2019). Lastly, Total Interpretive Structural Modeling **(TISM)** enhances ISM by adding interpretive reasoning behind structural linkages. The collation of these MCDM approaches signifies the ship recycling industry's nuanced approach towards balancing environmental (Env), economic (Eco), and social (Soc) sustainability goals, resonating with the triple bottom line approach, and targeting pivotal stakeholders such as ship owners, shipyards, and policymakers. This diverse toolkit, surfaced through diligent searches on scholarly platforms using precise keywords, underscores the dynamic application of MCDM to the critical trade-offs intrinsic to sustainable ship recycling practices.

The sustainability dimensions serve as the fundamental pillars upon which the assessment of sustainable practices in ship recycling is based. The environmental dimension scrutinizes the impact of ship recycling operations on the ecosystem, considering factors such as emissions, waste management, and the preservation of biodiversity. It is a critical gauge for measuring the ecological footprint of recycling processes and their compliance with environmental protection standards (Garg et al., 2023). In tandem with environmental considerations, the economic dimension evaluates the financial implications of ship recycling. This analysis delves into the profitability, cost-benefit ratios, and long-term economic sustainability of recycling practices, ensuring that environmentally conscious methods are also economically viable and contribute positively to the industry's growth (Keyghobadi et al., 2020). Complementing the environmental and economic facets is the social dimension, which assesses the human-centric aspects of ship recycling. It encompasses the welfare and safety of workers, the socio-economic impact on local communities, and the broader implications for society. Studies focusing on this dimension aim to ensure that the industry's growth is equitable and inclusive, adhering to social justice and labor rights (Akcan & Taş, 2019; Keyghobadi et al., 2020).

To gather this information, a systematic search was conducted on Google Scholar using keywords "EoL ships", "ship demolition, "ship dismantling," "ship recycling," and "MCDM." This targeted search was aimed at identifying pertinent scholarly articles and publications over the last twenty years, thus ensuring the inclusion of both seminal and contemporary research within this domain. This strategy facilitated the extraction of a comprehensive view of how MCDM methods have been employed to navigate the complex trade-offs between the various sustainability dimensions in the ship recycling industry.

2.4 Chapter Summary

This chapter provides an in-depth review of the **Ship-Recycling Industry**, emphasizing its connection with the **Circular Economy Framework**. Beginning with an extensive overview of the industry, it sheds light on the critical **Decision Factors**, prominent **Stakeholders**, standard **Procedures, And Methods** utilized in ship recycling. A significant aspect of the discussion revolves around the **EoL Material Composition** of ships, and how these materials are processed and reintroduced into the system. The chapter also introduces the concept of **Green Ship Recycling**, outlining the **Factors That Promote Environmentally Friendly Practices**, and identifying the **Sustainable Challenges** that hinder sustainability. A notable transition observed in this chapter was the shift from **LE to CE** in the context of ship recycling. The chapter delineates the **Limitations of The Circular Economy's Applicability** in this sector, emphasizing the pressing need for specialized strategies. Despite these limitations, compelling reasons for adopting a circular approach are evident, presenting a holistic view of a ship's life cycle. While the concept of circular economy is gaining momentum in various sectors, its unique application in ship recycling is still emerging. This chapter underscores the industry's distinct characteristics and the need for bespoke strategies that include comprehensive frameworks to close the material loop, optimize reverse supply chains, and evaluate the environmental and economic implications of these circular practices.

In summary, this chapter not only offers a panoramic view of the current state of the ship recycling industry but also highlights existing research gaps. It sets a solid foundation for the subsequent chapters of this thesis by emphasizing the transformative potential of the **Circular Economy** in making ship recycling a sustainable and economically sound industry.

Chapter 3: Problem Formulation & Model

In the realm of sustainable development and environmental conservation, the efficient management of EoL ships has emerged as a crucial challenge in recent years. As maritime industries grapple with mounting concerns regarding environmental impacts and resource depletion, the concept of CLSCN has gained significant attention as a potential solution. The problem of the supply chain network design for EoL ships is complex. There are many factors to consider, such as the location of the dismantling facilities, transportation of ships, recycling of materials, and reuse of components. In this section, we formulate the problem as a mathematical model and explain its assumptions. The model will be MILP. This type of model is well-suited for problems with many variables and constraints. The main objective of the model is to minimize the total cost of the closed-loop supply chain network, which is solved using a commercial solver. Through an intricate blend of theoretical frameworks, practical insights, and innovative methodologies, this study aims to pave the way for a sustainable and responsible approach to ship recycling and effective utilization of discarded vessel resources. By presenting an in-depth understanding of the problem at hand and the proposed modeling techniques, this chapter sets the stage for a transformative investigation into a more ecologically balanced and economically viable maritime industry.

3.1 Reverse Supply Chain Optimization Models

Today, it is widely acknowledged that Earth's resources are finite and that humans cannot continue to be as wasteful as they once were. Consequently, most supply chain processes have evolved beyond the traditional linear model of production and distribution for end users. The concept of reverse supply chains has evolved over time and its universal definition has been accepted by the scientific community. One of the most comprehensive definitions is "the process of planning, implementing, and controlling the backward flows of raw materials, work-in-process inventory, packaging, and finished goods from a manufacturing, distribution, or use point to a point of recovery or proper disposal" (Rubio et al., 2008). In addition to demanding high quality and competitive prices, customers are increasingly seeking environmentally friendly operations across the entire supply chain. Furthermore, new regulations place greater responsibility on manufacturers for the EoL phases of their products. Consequently, companies are facing increasing pressure to embrace sustainable practices. One effective approach to achieving this is through the design and implementation of a CLSC (Rentizelas and Trivyza, 2022). Reverse logistics are the nucleus of CLSCs. RL is integrated into the conventional supply chain process by accounting for both the forward and reverse product flows.

This approach is common because end users return products for various reasons, such as when they are no longer needed, when they are faulty, or when they do not meet their needs. The CLSC incorporates remanufacturing into the supply chain, which is the process of restoring returned products to new conditions for reselling (Rubio et al., 2008). CLSC management can be defined as the systematic design, control, and operation of a system that maximizes value creation throughout the product life cycle. This involves the dynamic recovery of values from various types and quantities of return over time. In a closed-loop supply chain, the flow of returned products from users must be integrated with a reprocessing stage to transform EoL products into usable products. This necessitates a shift from the traditional focus solely on the forward flow of materials to the consideration of the entire product lifecycle. It is crucial to expand the scope of the analysis to optimize the supply chain from a comprehensive cost perspective. Structural adjustments required for transitioning between different supply chain designs can be facilitated through frameworks such as viable and reconfigurable supply chains (Rentizelas et al., 2022).

Several studies have focused on the design of RL networks for EoL products (Demirel et al., 2016; John et al., 2018; Kilic et al., 2015; Liao, 2018; Rentizelas et al., 2022; Zhou and Zhou, 2015). As explained in Table 3 in Chapter 2, most studies do not specifically address EoL remanufacturing, highlighting the need for a CLSCN tailored to ship recycling. With the increasing significance of the circular economy, mounting regulatory pressures, and growing environmental consciousness, it has become crucial for shipping companies to adopt strategies that minimize environmental waste, recycle metal scrap, and repair and reuse the components from decommissioned vessels. The adoption of remanufacturing models in the shipbuilding industry holds the potential to optimize the CLSCN for EoL ships. Therefore, the design and implementation of a robust CLSCN are essential for establishing a framework for the remanufacturing processes in EoL ship management. A sustainable CLSCN should be developed to minimize the environmental impact of EoL ships and promote the reuse of dismantled ship components.

3.2 CLSCN Design Problem for EoL Ships

In the past two decades, there has been a notable surge in interest in academic and industrial sectors regarding CLSCN design problems. This heightened interest can be attributed to growing environmental consciousness and escalating regulatory and consumer pressure. The ambit of CLSC design encompasses decisions pertaining to facility location and capacity allocation within both the forward and reverse chains. This encompasses the effective and efficient management and coordination of physical flows occurring in both directions. Evidently, the CLSCN design problem exhibits variations across industries, reflecting the distinct characteristics inherent to each industry.

Notably, factors such as the duration of a product's life cycle, rate of technological advancement, and potential advantages associated with various recovery options must be carefully considered when formulating decisions regarding CLSC design. These factors directly affect the environmental and economic performance of a CLSC and subsequently influence its overall success and sustainability.

To transition towards a more sustainable and circular economy, there is a pressing need for an improved and efficient recovery process for EoL products and their various components and materials. A key component of this process is a well-executed disassembly that plays a vital role in enabling reuse, remanufacturing, high-value recycling, and implementation of other circular strategies. Recently, the rise of the CE model has highlighted the significance of supply network design as a pivotal element in transitioning towards a circular economy. Berlin et al. (2022) said the objective of achieving closed-loop systems in a circular economy is highly compatible with the concept of CLSCN, which has gained significant traction in recent times. Mannan et al. (2023) reviewed 143 SCOPUS documents and stated that during the last three decades, all articles related to ship recycling and dismantling have focused on breaking methods and an overview of the significant regulations that have passed over the years to ensure the sustainability of EoL ship recycling activities.

The recycling process of EoL ships is a complex and challenging task. It requires the sustainable dismantling, sorting, storing, recycling, and disposal of thousands of ship components. The dismantling process must be carried out in a way that minimizes the environmental impact. These include the use of environment-friendly dismantling techniques, recycling of materials, and disposal of hazardous waste. The sorted components must then be stored in a safe and organized manner. This will help to ensure that they are not lost or damaged. The recycled components can be used to remanufacture new ships and other products. This helps to reduce the demand for new materials and lowers the environmental impact of manufacturing. The disposed components must be handled in a way that minimizes the environmental impact. This may include burying the waste in landfills, recycling, or incineration. The proposed CLSCN structure for EoL ships is illustrated in Figure 27. Customers (CZs) play the dual role of suppliers, encompassing ship owners and ship breakers who provide EoL bulk carrier ships to ship dismantling yards within the system. In addition, the model shows the forward and reverse logistics activities for each phase.

In Phase 1, the utilized bulk carrier vessels are transferred from the Customer Zone (CZs) to the Ship Dismantling Yards (SDYs) at the owners' expense. In these centers, ships undergo disassembly, and their adherence to predefined standards is evaluated, dictating their subsequent destination, either a recycling facility or a metal processing facility. In Phase 2, the reusable components were individually separated at the SDYs and then transported to the Recycling Facility

(RFs) for further processing. Reusable components (i.e., machinery and electrical components) are dismantled, cleaned, overhauled, coated, and sent back to the SDYs for reassembly. In Phase 3, the ship's hull and other metal parts are transferred to the Metal Processing Facility (MPF), where the scrap metal must undergo a separation process, segregating it into ferrous, non-ferrous, and non-metallic components. Items such as engines, generators, navigation equipment, furniture, safety gear, and kitchen appliances can be refurbished and repurposed. Even propellers, anchors, and chains can be reconditioned for reuse or sold as scrap (Phase 4). In Phase 5 of the recycling process, ferrous scrap is typically separated from non-ferrous materials using an electromagnet. Ferrous scrap has extensive applications in steel mills and in the production of cast iron and steel. Metals that lack iron are categorized as non-ferrous. Non-ferrous alloys, including copper-based alloys, exhibit non-magnetic properties and excellent corrosion resistance. Owing to their magnetic properties, ferrous alloys can easily be identified using magnetic attraction. In the recycling process, ferrous scrap is typically separated from non-ferrous materials using an electromagnet. Subsequently, ferrous, and non-ferrous metals are transported to the recycling facility.

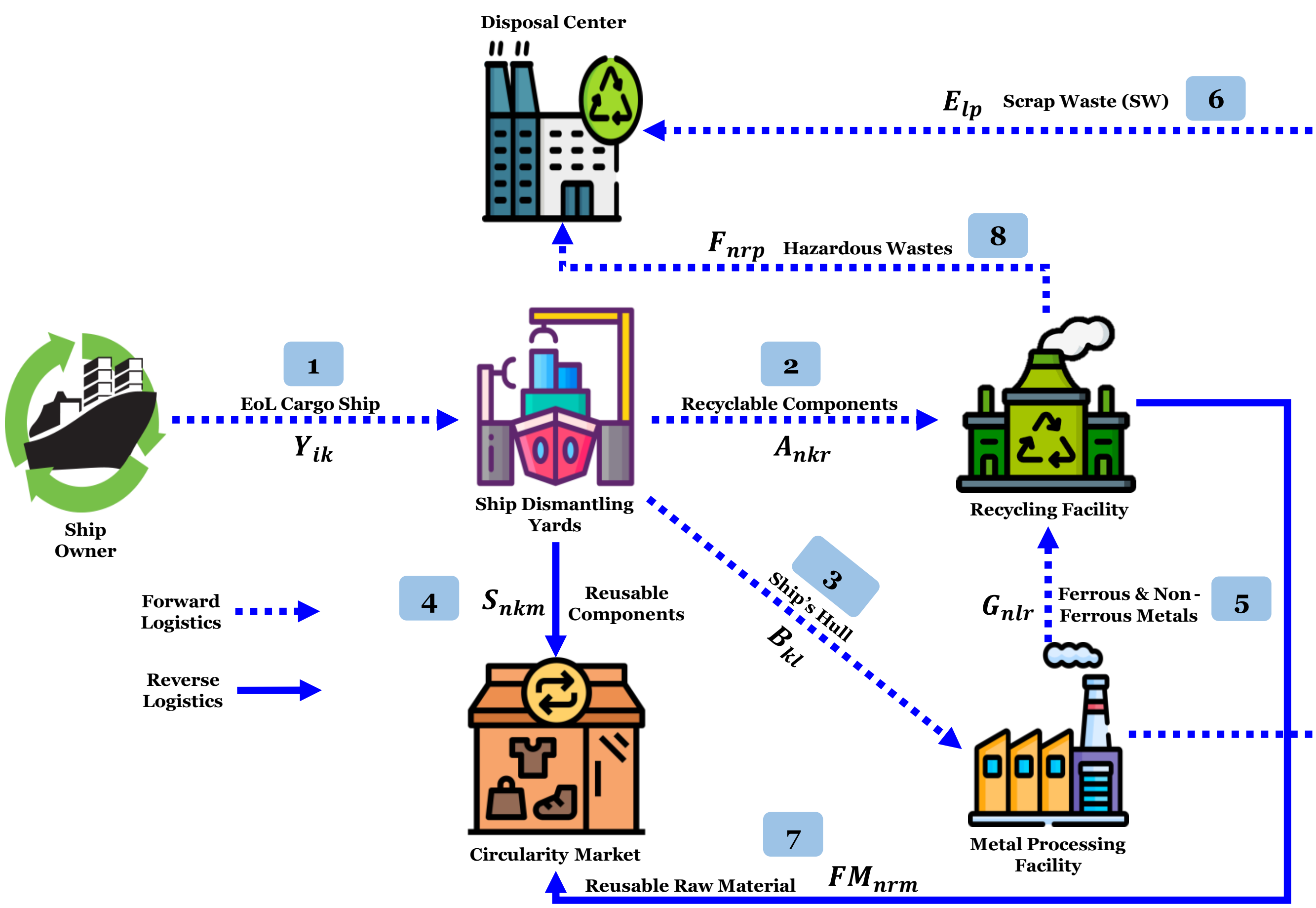


Figure 27. CLSCN Structure for EoL Ship

The scrap metal recycling industry transforms obsolete raw materials into high-quality, poverty-grade materials. Therefore, scrap metals undergo secondary refining after separation. Recycling facilities initially sort obsolete scrap into general categories; however, their precise chemical properties have not yet been determined. Purification is necessary to meet specific specifications for transforming scrap into viable raw materials. The solidified metal is then transported to the circularity market for reuse in various applications. As the ship's hull goes to shredders in the MPF, where the EoLS body is torn into pieces by shredding cylinders and blades, ferrous and non-ferrous metals are extracted. The rest of the shredded hull, called Shredder Waste (SW), which is composed of textiles, plastics, foam rubber, and insulators, has little economic value and is disposed of in landfill sites or burned out in cement factories (Phase 6). After performing the required processes on the recyclable components, they are sent to the secondhand market, and the revenue generated from the sale of these impaired parts re-enters the cycle (Phase 7). Phase 8 represents the transportation of hazardous waste that requires more complex recovery technologies (i.e., liquids, chemicals, and gases) to be shipped to (Disposal Center) DCs for recycling.

3.3 Mathematical Model Formulation

The shipbreaking industry is facing two key challenges. The first challenge is to reduce the amount of toxic waste released into the environment by adopting reverse logistics practices. The second challenge is to optimize the operational efficiency of a CLSCN to evaluate the economic feasibility and cost-effectiveness of ship recycling. The process of ship recycling, which involves the dismantling of decommissioned vessels and the remanufacturing of their recyclable components, presents a strategic opportunity to enhance sustainability within the maritime industry. To effectively repurpose end-of-life (EoL) ships into newer, operational vessels, it is essential to develop a Closed-Loop Supply Chain Network (CLSCN) that meticulously models the collection, distribution, and recycling processes. This network would not only streamline the transformation of old ships into valuable resources but also ensure that the intricate aspects of ship recycling, from environmental compliance to economic efficiency and resource optimization, are addressed comprehensively. An effective design of a CLSCN with reverse and forward logistics requires the application of sophisticated techniques, such as MILP, to optimize the total cost of remanufacturing. These mathematical techniques can enable decision makers to answer more complex questions, such as the number of ships that need to be dismantled to produce new ships annually? How many remanufacturing centers should be established to minimize all types of costs and reduce carbon emissions and energy consumption? The use of MILP and other mathematical techniques can help the ship-breaking industry address two key challenges and become more sustainable and cost-effective. The mathematical model for the reverse supply chain network proposed in this thesis is structured as a MILP model. It was inspired by the model of (Kuşakcı et al., 2019) in the EoL vehicles industry, with additional extensions and modifications to the original model. The objective of the model is to minimize the total cost and carbon emissions of the reverse supply chain network on an annual basis, determine the number and potential sites for metal processing facilities, ship dismantling yards, and optimal flow of products, and ensure adherence to specified constraints.

Table 8. Set and Indices

Set	Index	Description	Range
N	n	Components (Recyclable, Reusable, Recycled)	$n = 1,2,3 \dots . N$
I	i	Locations of Ship Owner	$i = 1,2,3 \dots . I$
K	k	Ships Dismantling Yards Locations	$k = 1,2,3 \dots . K$
L	l	Metal Processing Facility	$l = 1,2,3 \dots . L$
P	p	Disposal Centers	$p = 1,2,3 \dots . P$
R	r	Recycling Facility	$r = 1,2,3 \dots . R$
M	m	Circularity Markets	$m = 1,2,3 \dots . M$

The model explicitly incorporates all stages of the process, including waste retrieval, recycling, and the final delivery of the recycled product to the end user (in the circularity market). While the primary focus of the objective function is cost, the model also incorporates an analytical estimation of carbon emissions from each tier of the supply chain to provide an understanding of environmental impact. Table 8 presents the sets and indices, and Table 9 lists the decision variables of the model.

Table 9. Decision Variables

Symbol	Description	Variable Type	Unit
$\boldsymbol{A_{nkr}}$	Amount of subcomponent/material n of EoLS sent from SDY k to recycling facility r	Non-negative Variable	t/yr
$\boldsymbol{B_{kl}}$	Amount of ship's hull sent from SDY k to MPF l	Non-negative Variable	t/yr
$\boldsymbol{E_{lp}}$	Amount of SW sent from MPF l to DC p	Non-negative Variable	t/yr
$\boldsymbol{FM_{nrm}}$	Amount of material n sent from RF r to CM m	Non-negative Variable	t/yr
$\boldsymbol{F_{nrp}}$	Amount of material n sent from RF r to DC p	Non-negative Variable	t/yr
$\boldsymbol{G_{nlr}}$	Amount of subcomponent/material n sent from MPF l to RF r	Non-negative Variable	t/yr
$\boldsymbol{S_{nkm}}$	Amount of reusable subcomponent/material n of EoLS sent from SDY k to the CM m	Non-negative Variable	t/yr
$\boldsymbol{Y_{ik}}$	Weight of EoLS transferred from the last owner i to the SDY k	Non-negative Variable	t/yr
$\boldsymbol{e_l}$	One if the metal processing facility is open/used at location l; zero otherwise	Binary Variable	-
$\boldsymbol{e_k}$	One if the ship dismantling yard is used at location k; zero otherwise	Binary Variable	-

Equation (1) represents the multi-objective function of the CLSCN, where $Min\, TC$ represents the objective to minimize the total cost (TC). The total cost is a weighted sum of two components: the

Total Operational Cost (TOC) and the Total Environmental Cost (TEC). The weights Ψ_O and Ψ_E represent the importance given to the operational and environmental costs, respectively. The objective function hence balances the trade-off between these two costs in the minimization process. Equation 2 (Ψ = Sustainability Factor) represents the conditions involving the ratio of the weights Ψ_O and Ψ_E. When $\Psi > 1$, This condition indicates that the TOC is given more importance than the TEC in the optimization process. And vice versa when $\Psi < 1$. When $\Psi = 1$, indicates equal weighting for both costs, implying that the operational and environmental aspects are of equal importance in the optimization model. Equation 3 is used to monetize the environmental impact of emissions, converting the physical quantity of emissions into a financial metric that can be directly included in the overall cost optimization problem. ϒ is the conversion rate which according to (IMF BLOG, 2022) the EU has set the price at 90$ per ton. This enables a decision-maker to consider the carbon footprint in monetary terms, making it easier to weigh against other costs within the supply chain.

$$Min\,TC = \Psi_O\,TOC + \Psi_E\,TEC \tag{1}$$

$$\Psi = \Psi_O/\Psi_E \tag{2}$$

$$TEC = \Upsilon\,.\,TE \tag{3}$$

Equation 3 (T_E) is related to the total carbon emissions which focuses on reducing the CO_2 emissions during the transportation (T_E^1) (Equation 4), remanufacturing, disposal, recycling, and dismantling processes (T_E^2) (Equation 5). By integrating carbon reduction as an objective, the model helps balance economic goals with environmental considerations, which is crucial for the long-term success and sustainability of any operation.

$$T_E = T_E^1 + T_E^2 \tag{3}$$

$$\begin{aligned} T_E^1 = {} & \sum_{k=1}^{K}\sum_{l=1}^{L} D_{kl}B_{kl}CE_{trans} + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{r=1}^{R} D_{kr}A_{nkr}CE_{trans} + \sum_{n=1}^{N}\sum_{l=1}^{R}\sum_{r=1}^{R} D_{lr}G_{nlr}CE_{trans} \\ & + \sum_{l=1}^{L}\sum_{p=1}^{P} D_{lp}E_{lp}CE_{trans} + \sum_{n=1}^{N}\sum_{r=1}^{R}\sum_{p=1}^{P} D_{rp}F_{nrp}CE_{trans} \\ & + \sum_{n=1}^{N}\sum_{s=1}^{S}\sum_{m=1}^{M} D_{km}S_{nkm}CE_{trans} + \sum_{n=1}^{N}\sum_{r=1}^{R}\sum_{m=1}^{M} D_{rm}FM_{nrm}CE_{trans} \end{aligned} \tag{4}$$

$$\begin{aligned} T_E^2 = {} & \sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ik}CE_{nk} + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{r=1}^{R} A_{nkr}CE_{nr} + \sum_{n=1}^{N}\sum_{l=1}^{L}\sum_{r=1}^{R} G_{nlr}CE_{nr} + \sum_{n=1}^{N}\sum_{r=1}^{R}\sum_{p=1}^{P} F_{nrp}CE_{np} \\ & + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{l=1}^{L} B_{kl}CE_{nl} + \sum_{l=1}^{L}\sum_{n=1}^{N}\sum_{p=1}^{P} E_{lp}CE_{np} \end{aligned} \tag{5}$$

The primary rationale for including the reduction of CO_2 emissions in the objective function is the substantial environmental impact associated with the shipping industry, spanning from ship production through operation, maintenance and concluding with the dismantling phase. According to Chatzinikolaou and Ventikos (2014) the cumulative CO_2 emissions generated by a tanker ship over its entire lifecycle amount to approximately 1.10 million tons. Consequently, the dismantling phase emerged as the second most significant contributor to emissions within a ship's life cycle. Table 10 breaks down the total carbon emissions which generated from tanker ship.

Table 10. Total Life Cycle Carbon Emissions (Ship Type: Tanker)

Phase	Ship Building	Operation	Maintenance	Dismantling	Total Life Cycle
CO_2	2.29E+4	1.06E+6	9.62E+3	8.51E+3	1.10E+6

Next is the equation for the overall cost (Equation 6), which combines several elements. Equation (7) represents the sum of installation costs for SDYs, and metal processing facilities located at the chosen sites. In addition, the collection cost of the EoLS from the last owner is added to the equation. Equation (8) encompasses the total cost of disposal of SW and other hazardous materials and liquids. Equation (9) represents the total transportation cost associated with the subcomponents and materials extracted or imported across the entire network. Additionally, Equation (10) accounts for the total cost of disassembling, processing, disposal, and recycling the EoLS components and hulls. Finally, Equation (11) shows the total revenue generated by selling reused components and recycled material in the circularity markets.

$$T_C = T_C^1 + T_C^2 + T_C^3 + T_C^4 - T_R \tag{6}$$

$$T_C^1 = \sum_{l=1}^{L} f_l \,.\, e_l + \sum_{k=1}^{K} f_k \,.\, e_k + \sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ik} \,.\, CC_k \tag{7}$$

$$T_C^2 = \sum_{l=1}^{L}\sum_{p=1}^{P} E_{lp}.\, LC_p + \sum_{n=1}^{N}\sum_{r=1}^{R}\sum_{p=1}^{P} F_{nrp}.\, LC_p \tag{8}$$

$$\begin{aligned} T_C^3 = {} & \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{r=1}^{R} A_{nkr}.\, D_{kr}.\, t + \sum_{k=1}^{K}\sum_{l=1}^{l} B_{kl}.\, D_{kl}.\, t + \sum_{n=1}^{N}\sum_{l=1}^{L}\sum_{r=1}^{R} G_{nlr}.\, D_{lr}.\, t + \sum_{n=1}^{N}\sum_{r=1}^{R}\sum_{p=1}^{P} F_{nrp}.\, D_{rp}.\, t \\ & + \sum_{l=1}^{L}\sum_{p=1}^{P} E_{lp}.\, D_{lp}.\, t + \sum_{n=1}^{N}\sum_{r=1}^{R}\sum_{m=1}^{M} FM_{nrm}.\, D_{rm}.\, t \end{aligned} \tag{9}$$

$$T_C^4 = \sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ik}.\, DC_k + \sum_{k=1}^{K}\sum_{l=1}^{L} B_{kl}.\, SC_l + \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{r=1}^{R} A_{nkr}.\, RC_r + \sum_{n=1}^{N}\sum_{l=1}^{L}\sum_{r=1}^{R} G_{nlr}.\, RC_r \tag{10}$$

$$T_R = \sum_{n=1}^{N}\sum_{k=1}^{K}\sum_{m=1}^{M} S_{nkm}.UP_{nkm} + \sum_{n=1}^{N}\sum_{r=1}^{R}\sum_{m=1}^{M} FM_{nrm}.UP_{nrm} \quad (11)$$

Various constraints were formulated to ensure systematic flow of the materials. Constraint (12) dictates that the total amount of hull derived from the collected EoLSs in SDYs must be equal to the aggregate hull transferred to the metal processing facilities. The quantity of reusable subcomponents and materials obtained from SDYs and subsequently traded in circularity markets, which are substituted by new components from suppliers, must be equivalent (Constraint (13)). The combined quantity of recycled subcomponents and materials transported from SDY to the recycling center should match the portion of the total EoLS that is deemed unusable (Constraint (14)). Constraint (15) guarantees that the overall input of the SW into the metal processing facility is equivalent to the quantity it subsequently sends to the disposal center. Constraint (16) ensures that the aggregate quantity of ferrous and non-ferrous materials exiting the metal processing facility and entering the recycling center is equivalent to the combined quantity coming from the SDYs to the metal processing facility. The purpose of using the rat_n term in the constraints is to reflect the proportional representation of specific materials or components in the entire EoLS, allowing for more accurate calculations and considerations in the recycling and disposal processes. The constraints that don't use rat_n are addressing total amounts without the need to consider specific proportions.

Flow Constraints:

$$\sum_{l=1}^{L} B_{kl} = \alpha_1.\left(\sum_{i=1}^{I} Y_{ik}\right) \qquad \forall_k \in K \quad (12)$$

$$\sum_{k=1}^{K}\sum_{m=1}^{M} S_{nkm} = \alpha_2 \, . \, rat_n \, .\left(\sum_{i=1}^{I}\sum_{k=1}^{K} Y_{ik}\right) \qquad n = 8 \quad (13)$$

$$\sum_{r=1}^{R} A_{nkr} = \alpha_3 \, . \, rat_n \, .\left(\sum_{i=1}^{I} Y_{ik}\right) \qquad \forall_k \in K, \qquad n = 1,2, \dots 5 \quad (14)$$

$$\sum_{p=1}^{P} E_{lp} = \alpha_4 \, . \, rat_n \, .\left(\sum_{k=1}^{K} B_{kl}\right) \qquad \forall_l \in L, \qquad n = 3,4,5 \quad (15)$$

$$\sum_{r=1}^{R} G_{nlr} = \alpha_5 \, . \, rat_n \, .\left(\sum_{k=1}^{K} B_{kl}\right) \qquad \forall_l \in L, \qquad n = 6,7 \quad (16)$$

$$\sum_{p=1}^{P} F_{nrp} = \alpha_6 \, .\left(\sum_{k=1}^{K} A_{nkr}\right) \qquad \forall_r \in R, \qquad n = 1,2, \dots 5 \quad (17)$$

$$\sum_{p=1}^{P} F_{nrp} = \alpha_6 . \left(\sum_{l=1}^{L} G_{nlr}\right) \qquad \forall_r \in R, \qquad n = 6,7 \tag{18}$$

$$\sum_{m=1}^{M} FM_{nrm} = (1-\alpha_6) . \left(\sum_{l=1}^{L} A_{nkr}\right) \qquad \forall_r \in R, \qquad n = 1,2, \dots 5 \tag{19}$$

$$\sum_{m=1}^{M} FM_{nrm} = (1-\alpha_6) . \left(\sum_{l=1}^{L} G_{nlr}\right) \qquad \forall_r \in R, \qquad n = 6,7 \tag{20}$$

Constraint (17) guarantees that for every recycling center, the overall inflow of hazardous materials from each SDY must match the total outflow directed towards the disposal center. For every recycling center, the combined intake of hazardous materials originating from each MPF should be identical to the cumulative outflow directed toward the disposal center (Constraint (18)). Constraint (19) guarantees that, for every recycling center, the combined inflow of recyclable materials received from each SDY must match the total outflow directed toward the circularity market. For each recycling center, the overall intake of recyclable materials originating from every metal processing facility should be equal to the combined outflow directed toward the circularity market (Constraint (20)).

Capacity Constraints:

$$\sum_{i=1}^{I} Y_{ik} \leq cap_k . e_k \qquad \forall_k \in K \tag{21}$$

$$\sum_{k=1}^{K} B_{kl} \leq cap_l . e_l \qquad \forall_l \in L \tag{22}$$

$$\sum_{k=1}^{K} A_{nkr} + \sum_{l=1}^{L} G_{nlr} \leq cap_{nr} \qquad \forall_r \in R, \qquad n = 1,2, \dots 7 \tag{23}$$

$$\sum_{l=1}^{L} E_{lp} + \sum_{n=1}^{N}\sum_{r=1}^{R} F_{nrp} \leq cap_p \qquad \forall_p \in P \tag{24}$$

Non-negativity & Binary Constraints:

$$\left(Y_{ik},, S_{nkm}, A_{nkr}, B_{kl}, G_{nlr}, E_{lp}, F_{nrp}, FM_{nrm}\right) > 0 \qquad \forall\, i, k, m, n, r, l, p \tag{25}$$

$$e_k, e_l \in \{0,1\} \tag{26}$$

Constraint (21) ensures that the total inflow of EoLS to the SDY is limited by its capacity. Constraint (22) guarantees that the combined quantity of hulls being transported from the SDY to metal processing facilities must not surpass the capacity of the facility. The overall quantity of reusable subcomponents conveyed from the metal processing facility to each recycling center should not surpass the capacity of the center (Constraint (23)). The capacity of the disposal center is predefined and must not be exceeded (Constraint (24)). Non-negativity is ensured by constraint (25), and constraint (26) maintains binary variables to facilitate specific tasks.

Emissions Constraints:

$$\sum_{k=1}^{K}\sum_{l=1}^{L} D_{kl}B_{kl}CE_{trans} + \sum_{k=1}^{K}\sum_{r=1}^{R} D_{kr}A_{nkr}CE_{trans} + \sum_{l=1}^{R}\sum_{r=1}^{R} D_{lr}G_{nlr}CE_{trans} + \sum_{l=1}^{L}\sum_{p=1}^{P} D_{lp}E_{lp}CE_{trans} + \sum_{r=1}^{R}\sum_{p=1}^{P} D_{rp}F_{nrp}CE_{trans} + \sum_{s=1}^{S}\sum_{m=1}^{M} D_{km}S_{nkm}CE_{trans} + \sum_{r=1}^{R}\sum_{m=1}^{M} D_{rm}FM_{nrm}CE_{trans} \leq CE_{max} \quad \forall_n \in N \tag{27}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{n=1}^{N} Y_{ik}CE_{nk} + \sum_{n=1}^{n=5}\sum_{k=1}^{K}\sum_{r=1}^{R} A_{nkr}CE_{nr} + \sum_{n=6}^{n=7}\sum_{l=1}^{L}\sum_{r=1}^{R} G_{nlr}CE_{nr} + \sum_{n=1}^{n=7}\sum_{r=1}^{R}\sum_{p=1}^{P} F_{nrp}CE_{np} + \sum_{n=6}^{n=7}\sum_{k=1}^{K}\sum_{l=1}^{L} B_{kl}CE_{nl} \leq CE_{max} \tag{28}$$

Constraint (27) ensures that the CO_2 emissions generated from the transportation between facilities do not surpass the predetermined maximum threshold. Meanwhile, Constraint (28) serves to prevent the total CO_2 emissions from exceeding the maximum allowable limits during the various processes. Developing a mathematical model to analyze and optimize this integrated system requires the identification and incorporation of relevant parameters that capture the intricacies of these interconnected processes.

These parameters (Table 11) play a pivotal role in accurately representing various aspects of the circular economy, including the material flow, waste quantity, transportation cost, recycling efficiency, remanufacturing capacity, carbon emissions, and economic factors. By carefully defining and incorporating these parameters, the mathematical model can provide valuable insights into the optimization of circular economy practices, enabling informed decision-making and paving the way for more sustainable and resource-efficient recycling practices in the ship industry.

Table 11. Model Parameters

Symbol	Description	Unit
Capacity Parameters:		
CAP_k	Annual capacity of SDY k	ton
CAP_l	Annual capacity of metal processing facility l	ton
CAP_{nr}	Annual capacity of recycling facility r for EoLS subcomponent/ material n	ton
CAP_p	Annual capacity of disposal center p	ton
Distance Parameters:		
D_{kl}	Distance between SDY k and metal processing facility l	km
D_{kr}	Distance between SDY k and recycling facility r	km
D_{rk}	Distance between recycling facility r and SDY k	km
D_{lr}	Distance between metal processing facility l and recycling facility r	km
D_{lp}	Distance between metal processing facility l and disposal center p	km
D_{rp}	Distance between recycling facility r and disposal center p	km
D_{km}	Distance between SDY k and circularity market m	km
D_{rm}	Distance between recycling facility r and circularity market m	km
Cost Parameters:		
F_l	Opening cost of metal processing facility l	\$
F_k	Opening cost of SDY k	\$
CC_k	Collection & inspection costs of EoLS in SDY k	$\$/ton$
DC_k	Dismantling cost of EoLS in SDY k	$\$/ton$
SC_k	Processing cost in metal processing facility l	$\$/ton$
LC_p	Disposal cost at the disposal center p	$\$/ton$
RC_r	Recycling cost at the recycling facility r	$\$/ton$
t	Average transportation cost of components/materials within the network	$\frac{\$}{ton}/km$
Price Parameters:		
UP_{nkm}	Unit price of component/material n sent from SDY k to the circularity markets m	$\$/ton$
UP_{nrm}	Unit price of component/material n sent from recycling facility r to the circularity markets m	$\$/ton$

Emissions Parameters:		
CE_{max}	Maximum allowable total CO_2 emissions	$kgCO_2$
CE_{trans}	CO_2 emissions per km per ton during transportation	$\frac{kgCO_2}{(km \cdot ton)}$
CE_{nk}	CO_2 emissions that produced from component/material n at SDY k	$\frac{kgCO_2}{ton}$
CE_{nr}	CO_2 emissions that produced from component/material n at recycling facility r	$\frac{kgCO_2}{ton}$
CE_{np}	CO_2 emissions that produced from component/material n at disposal center p	$\frac{kgCO_2}{ton}$
CE_{nl}	CO_2 emissions that produced from component/material n at metal processing facility l	$\frac{kgCO_2}{ton}$
Ratio Parameters:		
α_1	Ratio of hull weight to whole EoLS weight ($0 \leq \alpha_1 \leq 1$)	-
α_2	Ratio of weight of reusable subcomponents/materials to whole EoLS weight ($0 \leq \alpha_2 \leq 1$)	-
α_3	Ratio of weight of non-reusable subcomponents/materials to whole EoLS weight ($\alpha_2 + \alpha_3 = 1$)	-
α_4	Ratio of weight of SW within the hull ($0 \leq \alpha_4 \leq 1$)	-
α_5	Ratio of recyclable materials within the hull ($0 \leq \alpha_5 \leq 1$)	-
α_6	Ratio of disposed materials within the recycled material ($0 \leq \alpha_6 \leq 1$)	-
rat_n	Ratio of the weight of component/material n to whole EoLS weight	-

3.4 Model Assumptions

When developing a model to analyze the circular economy of the ship recycling industry, it is important to establish a set of assumptions to guide the modeling process. The assumptions below serve as simplifications for real-world complexities and help define the scope and boundaries of the model.

Assumption 1) Limited Remanufacturing Scope: This assumption posits that remanufacturing activities within the CLSCN are confined to the structural and metal components of EoL ships, excluding electronic parts. This restriction simplifies the model by focusing solely on the recycling and reuse of physical materials and components while excluding the complexities associated with electronic waste handling and remanufacturing. However, it is worth noting that any usable electronic component will be directed to circularity markets, and suppliers will furnish new components.

Assumption 2) Homogeneous Transportation Fleet: the fleet of vehicles used to transport parts and products within the CLSCN is homogeneous. This means that all vehicles in the fleet have uniform characteristics such as capacity, fuel efficiency, and emission profiles. Real-world fleets may consist of diverse vehicle types; assuming homogeneity at the modeling stage simplifies the logistics, route planning, and scheduling aspects.

Assumption 3) Absence of Geographical Constraints: This assumption assumes that there are no significant geographical or topological constraints affecting transportation routes or placement of recycling and processing facilities within the CLSCN. By neglecting real-world complexities such as road conditions, traffic, or natural barriers, this assumption allows for a more straightforward and idealized network design in the model.

Assumption 4) Condition-based Recycling: This assumption suggests that certain ship components will be directed to recycling facilities for refurbishment and potential reuse only if their conditions permit. It acknowledges that not all components may be suitable for reuse, and that the decision to recycle or refurbish depends on the state of the component.

Assumption 5) Predetermined Reverse Flow Ratios: It predefines the reverse flow ratios for each subcomponent and material collected from EoL ships. These ratios specify the proportion of materials that are recycled, remanufactured, or otherwise processed within the CLSCN. Having predetermined ratios simplifies decision making within the model but may not fully capture the dynamic nature of material flows in real-world scenarios.

Assumption 6) Facility Locations Based on Authorization: Here assumed that the prospective sites for all facilities (recycling, processing, etc.) are determined primarily by considering the presence of currently authorized facilities. This simplifies the site selection process by assuming that regulatory and permitting constraints are the primary factors that influence facility locations.

Assumption 7) All components (including machinery components) sent to the circularity markets are sold according to their weight, a detail that is further elaborated and evidenced in Table 20.

3.5 Case Study Selection and Dataset

The EU-27 and UK were chosen as the macro levels in this study for several reasons. First, the EU and the UK have a harmonized regulatory framework for the dismantling and recycling of EoL ships. This ensures that all member states have the same standards and requirements, which facilitates cross-border movement of dismantled and recycled materials. Second, the EU is a significant player in the global ship recycling market with a substantial fleet and commitment to sustainable practices. This region not only accounts for a substantial portion of the world's ship dismantling activities but also has stringent environmental and labor regulations in place. Moreover, the EU's influential position in global maritime trade and environmental policy can provide a powerful example for other regions, encouraging the adoption of similar practices worldwide. Third, the EU has the largest number of dismantling ships and metal recycling facilities worldwide (Figure 28). The subsequent figures show the positions of various model components, including disposal centers, recycling facilities, suppliers of ship parts, and markets for used products. Furthermore, the EU's preeminence in the ship recycling industry is underscored by its possession of the highest quantity of recycling facilities worldwide. This substantial infrastructure, comprising of numerous certified recyclers strategically located across EU member states, plays a pivotal role in the sustainable dismantling of ships.

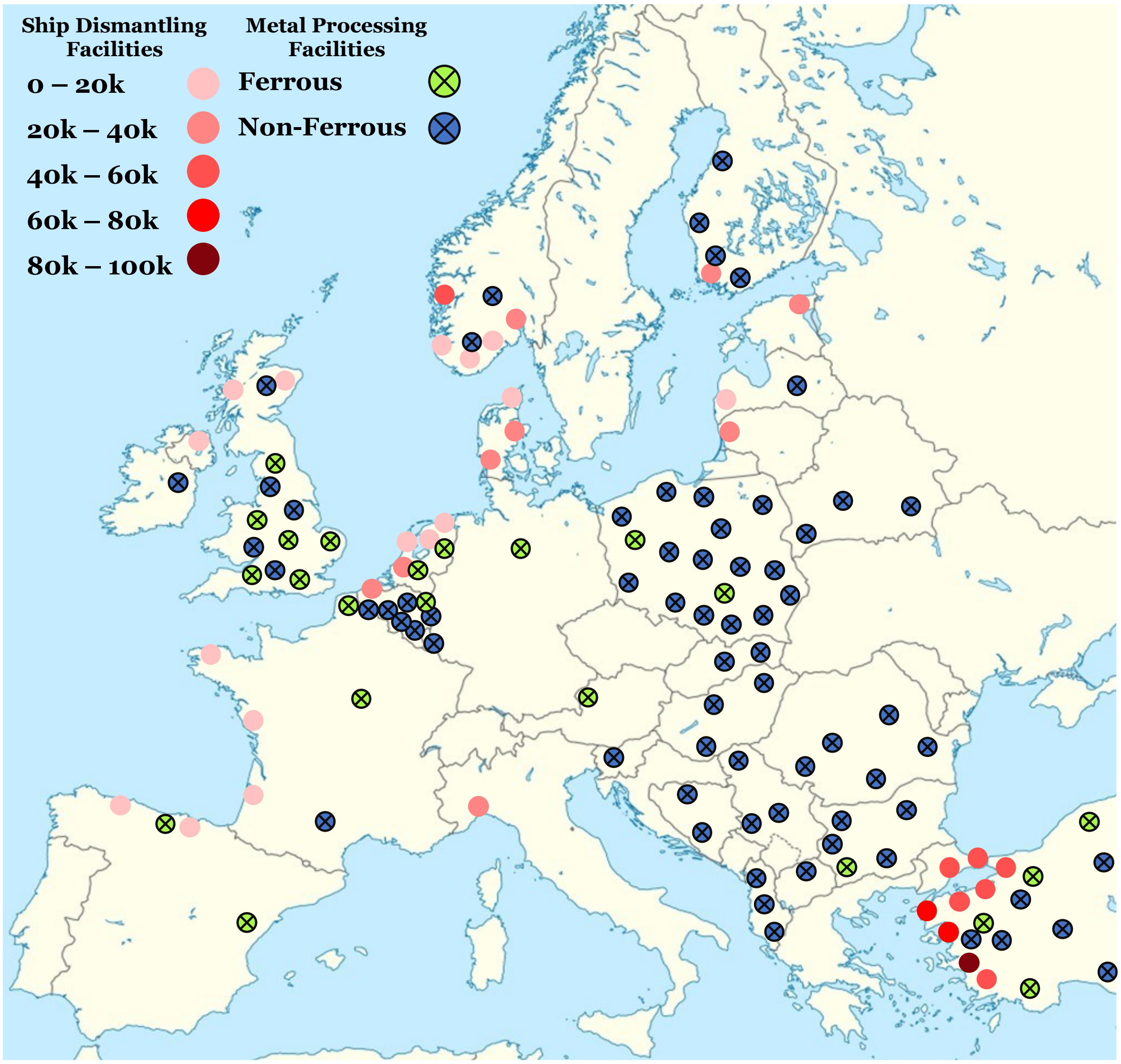


Figure 28. Ship Dismantling and Metal Processing Facilities Locations in Europe
Data Source (Ship Dismantling Facilities): [9th Edition of The European List of Ship Recycling Facilities]
Data Source (Metal Processing Facilities): https://www.enfmetal.com/directory/plant/Other-Europe

Figure 29 provides a visual representation of this extensive network and offers valuable insights into the scale of these facilities and their estimated capacities. In the chart, color coding is employed to denote the capacity of each certified recycler, allowing for a quick and comprehensive assessment of the region's ship-recycling capabilities. This unparalleled network of recycling facilities within the EU not only demonstrates the region's commitment to environmentally responsible ship dismantling, but also underscores the practical feasibility of CLSCN implementation in the European ship recycling sector. It positions the EU as a leader in shaping the global ship-recycling industry toward a more sustainable and ethical future.

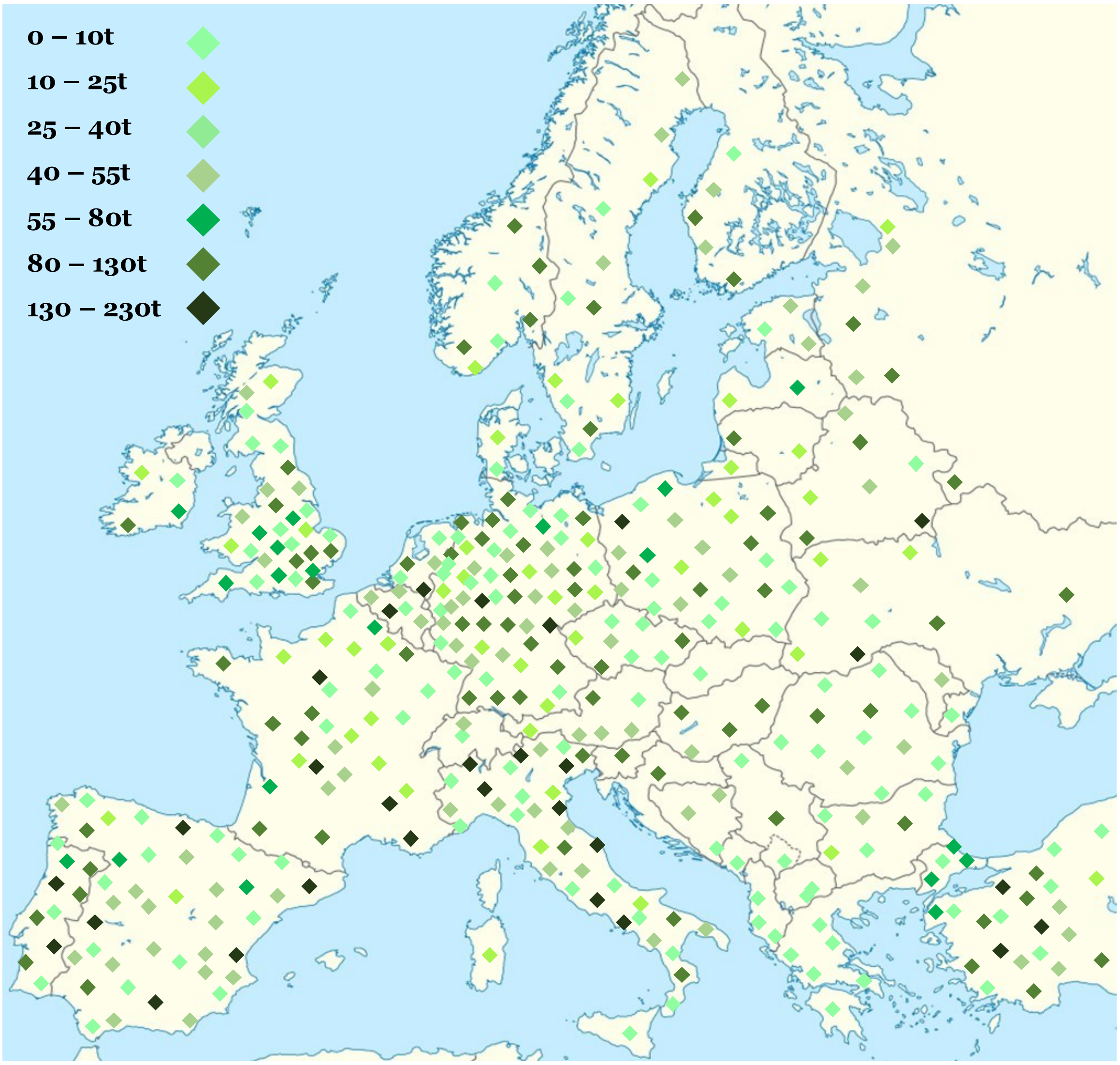


Figure 29. Recycling Facilities Locations in Europe
Data Source: https://www.eucertplast.eu/certified-recyclers

According to the EEA (European Environment Agency), there are 1863 disposal facilities and 278 landfill locations. companies that manage the treatment of hazardous wastes. It was difficult to draw more than 2000 locations on the map below. Figure 30 shows the estimated locations of the main disposal facilities in the EU. However, the map provides a tangible representation of the distribution of these facilities across countries. Notably, Germany, Italy, France, and Spain stand out as countries with the most extensive number of such facilities. Conversely, countries such as Iceland, Liechtenstein, and Luxembourg report very limited numbers of facilities. This discrepancy arises because these countries are relatively small and produce only a limited amount of hazardous waste, which is often managed by neighboring nations. For instance, Liechtenstein's disposal system is integrated into Switzerland's disposal system, while Luxembourg primarily disposes of a significant portion of its hazardous waste in France, Belgium, and Germany.

Figure 30. Disposal Facilities and Landfills Locations in Europe
Data Source: https://www.eea.europa.eu/publications/Technical_report_no_65/download

Figure 31 provides a comprehensive visual representation of the strategic distribution of ship component suppliers in the EU (95 locations). Each marked location on the map represents a vital node in the supply chain network where various critical ship parts and components originate. These suppliers play an integral role in supporting shipbuilding, repair, and maintenance sectors. Additionally, the map shows the locations of the secondhand markets for the machinery used. Italy and Germany stand out as the countries with the most extensive numbers of such locations.

Figure 31. Circularity Markets Locations in Europe
Data Source: https://www.europages.co.uk/companies/usedmachinesforships.html

According to a report by Allied Market Research (2021), the global shipbuilding market reached USD 142.52 billion in 2020 and is anticipated to achieve USD 195.48 billion by 2030. This projection signifies a Compound Annual Growth Rate (CAGR) of 3.2% from 2021 to 2030. Furthermore, as per a report by Mordor Intelligence (2023), the shipbuilding market is currently estimated to be USD 145.67 billion by 2023, with expectations to reach USD 184.50 billion by 2028. This projection represents a CAGR of 4.84% during the forecast period spanning from 2023 to 2028. Figure 32 shows this trend for each year during the same period.

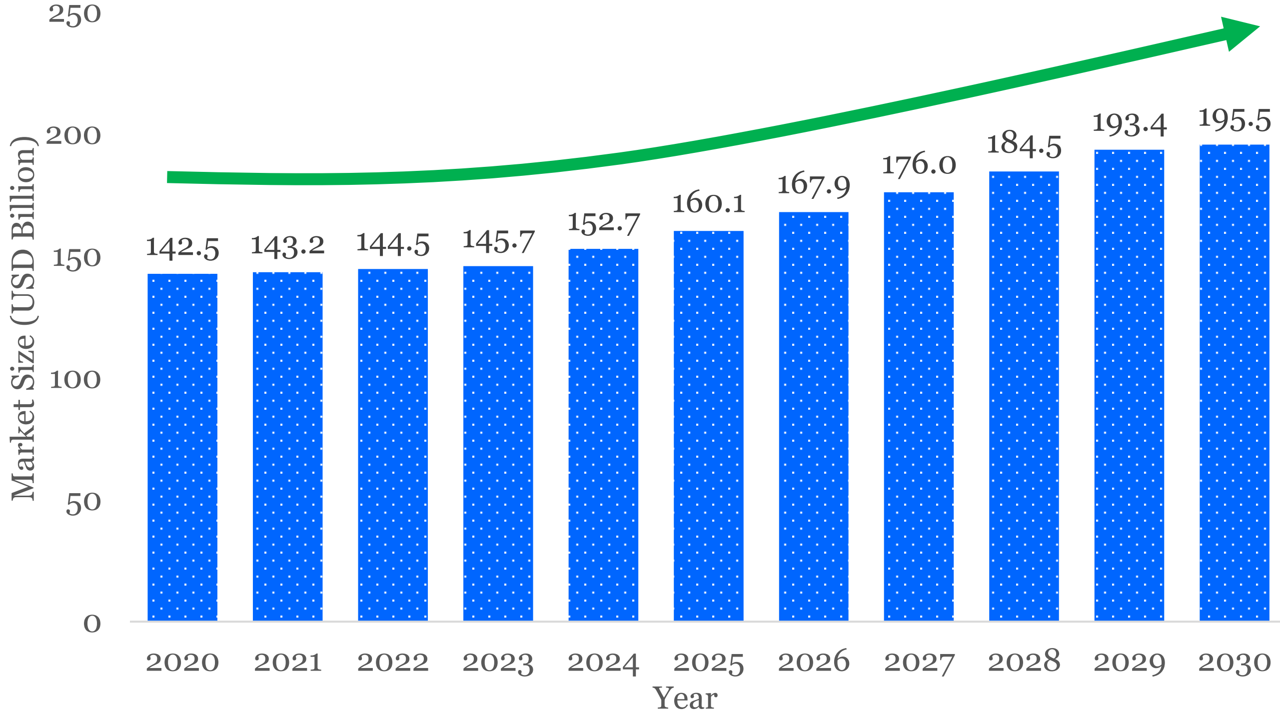


Figure 32. Ship Building Market Size Trend from 2020 to 2030
Data Source: (Allied Market Research, 2021; Mordor Intelligence, 2023)

Prominent catalysts propelling the expansion of the global shipbuilding industry include factors such as the escalation of GDP, enhanced economic development, upsurge in global maritime commerce, heightened demand for cargo conveyance via ships, proliferation of trade agreements, progressive advancements in marine vessel propulsion technology, and adoption of automation trends within marine transportation. Nevertheless, it's worth noting that fluctuations in transportation and inventory costs, in conjunction with environmental apprehensions linked to marine vessels, represent notable trends that have the potential to impede market growth.

3.6 Data Collection and Scope

The data used in this thesis were collected by the NGO Shipbreaking Platform, a global organization that advocates safe and environmentally sound shipbreaking practices (NGO Shipbreaking Platform, 2022). In addition, data were collected from various sources, including academic journals, government reports, and industry publications. The data were limited in some cases because there is little research on the circular economy in the ship recycling industry or similar industries. Despite this, the data sources used in this study provide valuable insights into the current state of circular economy in ship recycling. Table 12 lists the estimated average values of the model parameters.

Note: * In the ship-breaking industry, is the light displacement tonnage, which, in simple terms, is the weight of water displaced by the ship – the mass of the ship excluding cargo, fuel, ballast, stores, passengers, and crew, but with water in boilers to steaming level.

Table 12. Model Parameters Estimated Values

Symbol	Description	Estimated Value
Capacity Parameters:		
CAP_k	Ship Dismantling Facility Annual Capacity	$50000\ LDT^*/year$
CAP_l	Metal Processing Facility Annual Capacity	$80000\ ton/year$
CAP_{nr}	Recycling Facility Annual Capacity	$70000\ ton/year$
CAP_p	Disposal Center Annual Capacity	$15000\ ton/year$
Cost Parameters:		
F_l	Opening Cost of Metal Processing Facility	$1.5 * 10^6$ \$
F_k	Opening Cost of SDY	$3 * 10^6$ \$
CC_k	Collection Cost of EoLS	$500\ \$/ton$
DC_k	Dismantling Cost of EoLS	$700\ \$/ton$
SC_k	Processing Cost in Metal Processing Facility	$500\ \$/ton$
LC_p	Disposal Cost at the Disposal Center	$150\ \$/ton$
RC_r	Recycling Cost at the Recycling Facility	$200\ \$/ton$
t	Average Transportation Cost	$0.5\ \$/ton.km$
Price Parameters:		
UP_{nkm}	Unit price of material sent from SDY to the circularity markets	$5000\ \$/ton$
UP_{nrm}	Unit price of material sent from recycling facility to the circularity markets	$850\ \$/ton$
Emissions Parameters:		
CE_{max}	Maximum allowable total CO_2 emissions	$50000\ kgCO_2$
CE_{trans}	CO_2 emissions per km per ton during transportation	$0.06\ kgCO_2/ton.km$
CE_{nk}	CO_2 emissions that are produced at SDY	$2\ kgCO_2/ton$
CE_{nr}	CO_2 emissions that are produced at recycling facility	$5\ kgCO_2/ton$
CE_{np}	CO_2 emissions that are produced at disposal center	$3\ kgCO_2/ton$
CE_{nl}	CO_2 emissions that are produced at metal processing facility	$5\ kgCO_2/ton$
Ratio Parameters:		
α_1	Ratio of Hull Weight to Whole EoLS Weight	0.9
α_2	Reusable Subcomponents/Materials to Whole EoLS Weight	0.75
α_3	Non-Reusable Subcomponents/Materials to Whole EoLS Weight	0.25
α_4	The Weight of SW Within the Hull	0.3
α_5	Recyclable Materials Within the Hull	0.9
α_6	Disposed Materials Within the Recycled Material	0.1
rat_n	The Weight of Component/Material n to Whole EoLS Weight	0.1

Data Sources: https://www.eea.europa.eu/en/analysis, https://worldsteel.org/steel-topics/statistics/ , https://www.imo.org/en/publications/Pages/Home.aspx, https://www.worldshipping.org/ , https://www.shiprecyclingtransparency.org/explore-srti-data/

As previously mentioned, this model is illustrative in nature, and all incorporated values are average estimates derived from industry reports on websites. Various factors influence each parameter group.

Concerning the capacity parameters, factors such as location, labor costs, vessel type, and environmental and safety regulations dictate the facility's capacity. In relation to emission parameters, elements such as the type of material, equipment, and technology used, the size and type of the facility, and the operational setup play significant roles. As illustrated in Figure 28, several European nations, including Türkiye, France, Belgium, Norway, and the Netherlands (predominantly coastal countries), have engaged in the ship dismantling sector. Given the intricacies of the model, paired with a multitude of locations encompassing metal recycling facilities, disposal centers, circularity markets, and suppliers across the EU, this study focuses on Türkiye. Notably, it stands out for having the highest number of ships dismantling yards in Europe, aligning with the primary intent of our model. Furthermore, Türkiye encompasses all the vital factors of our model, ranging from recycling facilities and disposal centers to suppliers and a robust circularity market for industrial apparatus.

Table 13. Estimated Distance Matrix for Parameter D_{kl} (km)

Distance between SDY k and MPF l					
	l_1	l_2	l_3	l_4	l_5
k_1	223	553	713	616	864
k_2	286	378	674	577	783
k_3	448	138	342	496	651
k_4	486	152	295	441	548
k_5	578	225	275	338	518
k_6	612	312	246	283	493
k_7	886	462	316	89	146
k_8	924	572	394	137	97
k_9	980	671	571	267	132

Distance parameters played a pivotal role in this study. The associated tables explain these distance parameters and capture the spatial relationships among various entities in the supply chain. These distances, represented in the tables, quantify the geographical separation between ship dismantling yards, recycling facilities, disposal centers, and circularity markets (Tables 12–19).

Table 14. Estimated Distance Matrix for Parameter D_{kr} (km)

Distance between SDY k and RF r					
	r_1	r_2	r_3	r_4	r_5
k_1	133	573	513	616	884
k_2	73	368	474	567	793
k_3	438	156	142	486	671
k_4	476	92	121	431	538
k_5	588	115	225	358	528
k_6	622	142	266	383	483
k_7	886	452	312	189	126
k_8	934	566	376	231	97
k_9	990	689	581	277	79

By integrating these distance metrics into our model, we aim to provide a nuanced understanding of logistical challenges and facilitate optimal decision making for efficient and sustainable operations within the ship recycling industry. This approach empowers the model to propose solutions that reflect real-world constraints and are feasible for academic analysis.

Table 15. Estimated Distance Matrix for Parameter D_{lr} (km)

Distance between MPF l and RF r					
	r_1	r_2	r_3	r_4	r_5
l_1	118	337	448	559	782
l_2	388	115	78	151	332
l_3	435	107	105	96	288
l_4	477	159	145	112	252
l_5	580	231	185	128	105

It helps in determining transportation costs and optimizing the movement of recovered metals for recycling purposes. Table 16 highlights the distances between the metal facilities and disposal centers. Disposal centers handle waste that isn't recyclable or reusable.

Table 16. Estimated Distance Matrix for Parameter D_{lp} (km)

Distance between MPF l and DC p					
	p_1	p_2	p_3	p_4	p_5
l_1	115	501	672	623	769
l_2	387	139	630	189	492
l_3	407	118	553	148	349
l_4	444	127	313	114	328
l_5	486	222	479	98	134

Therefore, understanding the distance between metal facilities (where potentially non-recyclable residues are generated) and disposal sites is fundamental for assessing the environmental impacts and costs related to waste transportation and disposal.

Table 17. Estimated Distance Matrix for Parameter D_{rp} (km)

Distance between RF r and DC p					
	p_1	p_2	p_3	p_4	p_5
r_1	112	451	358	571	655
r_2	356	129	186	216	369
r_3	406	152	104	154	283
r_4	563	166	157	87	156
r_5	797	371	368	114	95

Table 16 presents the geographical distances between the recycling facilities and disposal centers. This matrix ensures that waste from recycling facilities that cannot be processed further is efficiently transported to disposal sites.

Table 18. Estimated Distance Matrix for Parameter D_{km} (km)

Distance between SDY k and CM m															
	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}	m_{11}	m_{12}	m_{13}	m_{14}	m_{15}
k_1	72	106	128	144	89	191	281	295	310	322	345	361	392	423	488
k_2	105	125	185	124	73	115	189	203	224	265	278	288	301	329	365
k_3	188	194	225	230	159	84	142	168	182	201	216	232	251	264	321
k_4	245	269	315	285	267	234	104	88	96	113	142	182	230	251	288
k_5	322	348	389	325	311	219	118	78	79	132	172	186	244	267	318
k_6	351	378	466	447	427	247	126	113	97	141	192	207	272	293	340
k_7	603	638	664	582	563	310	152	163	144	126	76	66	117	102	178
k_8	636	647	668	622	608	579	313	334	317	234	178	87	111	93	150
k_9	680	716	745	685	661	585	411	447	413	277	196	130	105	68	118

Efficient planning can minimize the ecological footprint and transportation costs associated with the disposal of non-recyclable residues. Table 18 illustrates the distances between the SDYs and various circularity markets. This matrix is vital for optimizing transportation routes, aiding strategic planning regarding the location of SDYs, and promoting eco-friendly logistics by minimizing transportation distances and the associated carbon footprint. Table 19 highlights the relationship between recycling facilities and circularity markets in the ship dismantling industry. It streamlines waste management by guiding the efficient movement of residues, fosters sustainability by reducing transit distances and the associated environmental impacts, and offers potential transportation cost savings.

Table 19. Estimated Distance Matrix for Parameter D_{rm} (km)

Distance between RF r and CM m															
	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}	m_{11}	m_{12}	m_{13}	m_{14}	m_{15}
r_1	125	179	211	117	47	176	246	264	280	299	311	334	376	410	560
r_2	499	518	547	568	509	280	113	78	103	145	166	188	259	281	388
r_3	572	597	616	465	441	321	57	133	145	142	155	188	229	272	344
r_4	594	622	653	627	615	343	124	156	125	142	111	163	181	209	328
r_5	681	638	641	633	611	562	489	518	465	448	381	204	70	95	119

Table 20. Market Prices of Reusable Components and Recycled Materials

	Plastic (n_1)	**Glass (n_2)**	**Fluids (n_3)**	**Minerals (n_4)**	**Joinery (n_5)**	**Ferrous Metal (n_6)**	**Non-Ferrous Metal (n_7)**	**Machinery (n_8)**
UP_{nkm}	300	350	200	250	250	—	—	850
UP_{nrm}	250	350	450	350	250	550	650	—

A bulk carrier EoLS weighing 10,000 kg can be broken down into various components based on the following percentages:85% ferrous metals, 7% machinery, 2.5% minerals, 1.3% joinery, 1.25% electronics, 1.2% plastics, 1% non-ferrous metals, 1% fluids, and 1% glass (Jain et al., 2017). After removing the reusable components, the remaining hull comprised 87% of EoLS. The market values of the reusable components and valuable materials obtained from the dismantling yards and recycling centers are listed in Table 20 (Secondary Data)(EUROSTAT, 2021).

3.7 Chapter Summary

This chapter delves deeply into the intricacies of problem formulation and modeling within the realm of circular economy principles in the ship recycling industry. This chapter introduces the **RSC Optimization Models**, highlighting the underlying strategies for achieving optimal resource utilization in ship recycling. This is complemented by a distinct section on the **CLSCN Design Problem for EoL Ships** that addresses the challenges and opportunities specific to the lifecycle stages of these vessels.

The heart of this chapter is the **Mathematical Model Formulation**, which details the analytical framework devised to scrutinize and fine-tune an integrated recycling system. This model factors myriad variables, such as material flows, transportation dynamics, and the dual impact metrics of environmental and economic performance. To bolster the validity of this model, a subsequent section elucidates the **Model Assumptions**, ensuring clarity on the foundational principles and constraints.

Offering a practical perspective, the chapter then ventures into the **Case Study Selection and Dataset**, focusing on the estimated datasets that can be applied to the mathematical model. The decision to rely on estimated data is the lack of real-world data. Rounding off the chapter is a section on **Data Collection and Scope**, which delineates the sources, extent, and nuances of data gathering, setting a clear boundary on the study's purview. As previously mentioned, Türkiye was selected as the focus of this study.

Chapter 3 charts the course for a rigorous and comprehensive exploration of circular economy tenets in the ship recycling domain. This serves as a robust foundation, priming the reader for subsequent in-depth analyses and insights into sustainable recycling practices.

Chapter 4: Results and Discussion

The results section of this thesis provides a comprehensive analysis and evaluation of the circular economy in the integrated system of the ship recycling industry. This study aims to assess the feasibility, effectiveness, and sustainability of implementing circular economy practices in interconnected industries. Through the application of mathematical modeling and data analysis, the results shed light on various aspects, including material flows, resource utilization, economic performance, environmental impacts, and regulatory compliance. Moreover, the results offer insights into the optimization of processes, supply chain coordination, and the potential for cross-sector material exchanges. By examining the outcomes of different scenarios and considering key performance indicators, the results provide valuable guidance for policymakers, industry stakeholders, and practitioners to make informed decisions and develop strategies for enhancing circular economy practices in the ship recycling sector. As delineated in Figure 17, the diagram articulates the array of decisions available to a ship owner within the context of green ship recycling. The problem is approached from the vantage point of the ship owner, whose objective is to minimize the total cost while adhering to environmentally responsible recycling practices.

4.1 Optimal Network Design

In the pursuit of a sustainable future, the ship recycling industry stands at a crossroads and is tasked with balancing the demands of economic efficiency and environmental responsibility. Within this dynamic landscape, the concept of a closed-loop supply chain network has emerged as a beacon of innovation and transformative potential. The optimal design of such a network is key to unlocking the enhanced sustainability, profitability, and operational efficiency of the ship recycling sector. This section of the thesis embarks on a journey into the heart of network design, exploring the intricate web of decisions that shapes the closed-loop supply chain in ship recycling. By delving into the complexities of network design and its implications for resource allocation, transportation logistics, and environmental impacts, this study aims to provide a comprehensive framework for optimizing the closed-loop supply chain in the ship recycling industry. Through a synthesis of mathematical models, operational strategies, and sustainability objectives, this section seeks to pave the way for a new era of environmentally conscious and economically viable ship recycling practices.

Figure 33 presents an intricate and detailed optimal network design within the ship recycling industry, emphasizing the symbiotic relationship between reverse and forward logistics in the Aegean region of Türkiye. The map illustrates several key facilities, such as metal processing, suppliers, circularity markets, recycling facilities, and disposal centers, each distinctly represented by unique symbols. Forward logistics pathways, depicted by dotted lines, seem to facilitate the flow from suppliers towards metal processing and disposal centers. Conversely, the solid lines representing reverse logistics indicate the flow from disposal centers and circularity markets towards recycling facilities and back to suppliers, emphasizing the circular nature of the supply chain. The dense interconnectivity among various entities, coupled with the intertwined forward and reverse logistics, underscores the complexity of the CLSCN in the ship recycling industry. This design underscores the importance of integrating supply directions to achieve sustainability, resource optimization, and economic efficiency in the industry. In the subsequent sections, we decompose this extensive network into more granular subnetworks, providing a deeper analysis and explanation.

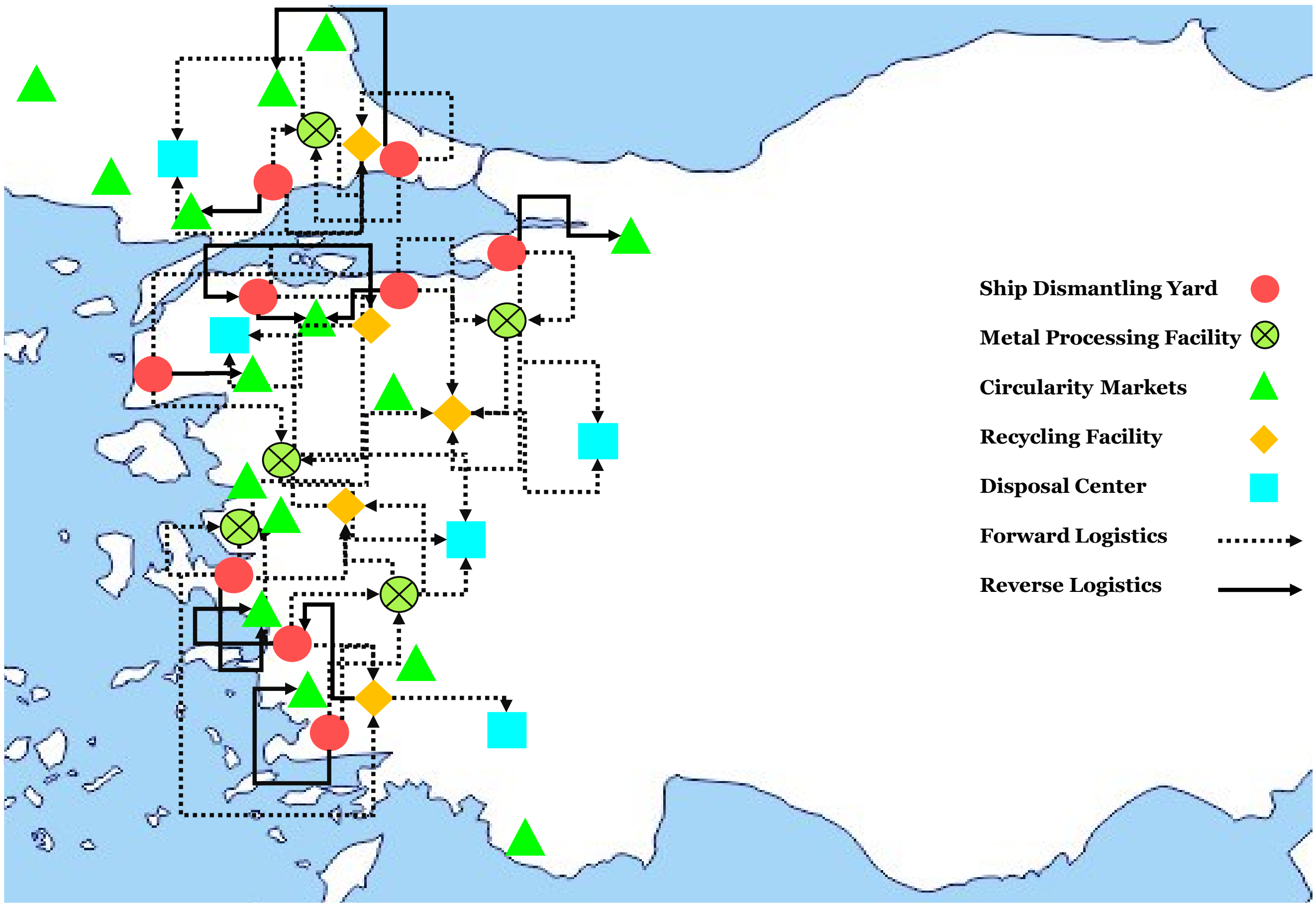


Figure 33. Optimal Network Design with Reverse and Forward Logistics

According to the optimum solution of the model and using the estimated values for all parameters, all nine SDYs and five metal recycling facilities must be used. For the observed EoLS flow and metal composite within the network, the SDYs operated at an average capacity of 91%, whereas the MPFs utilized an average rate of 98% (See Table 21). This phase might become a potential bottleneck for the entire network because of its high utilization percentages. Consequently, decision makers should focus on this issue. Figure 34 shows the flow of EoLSs in terms of LDT from SDY to MPF. The geographic distribution was strategically scattered. This proves that a robust infrastructure is in place to ensure that the EoLS can be effectively processed from various points without concentrating the load on a single facility.

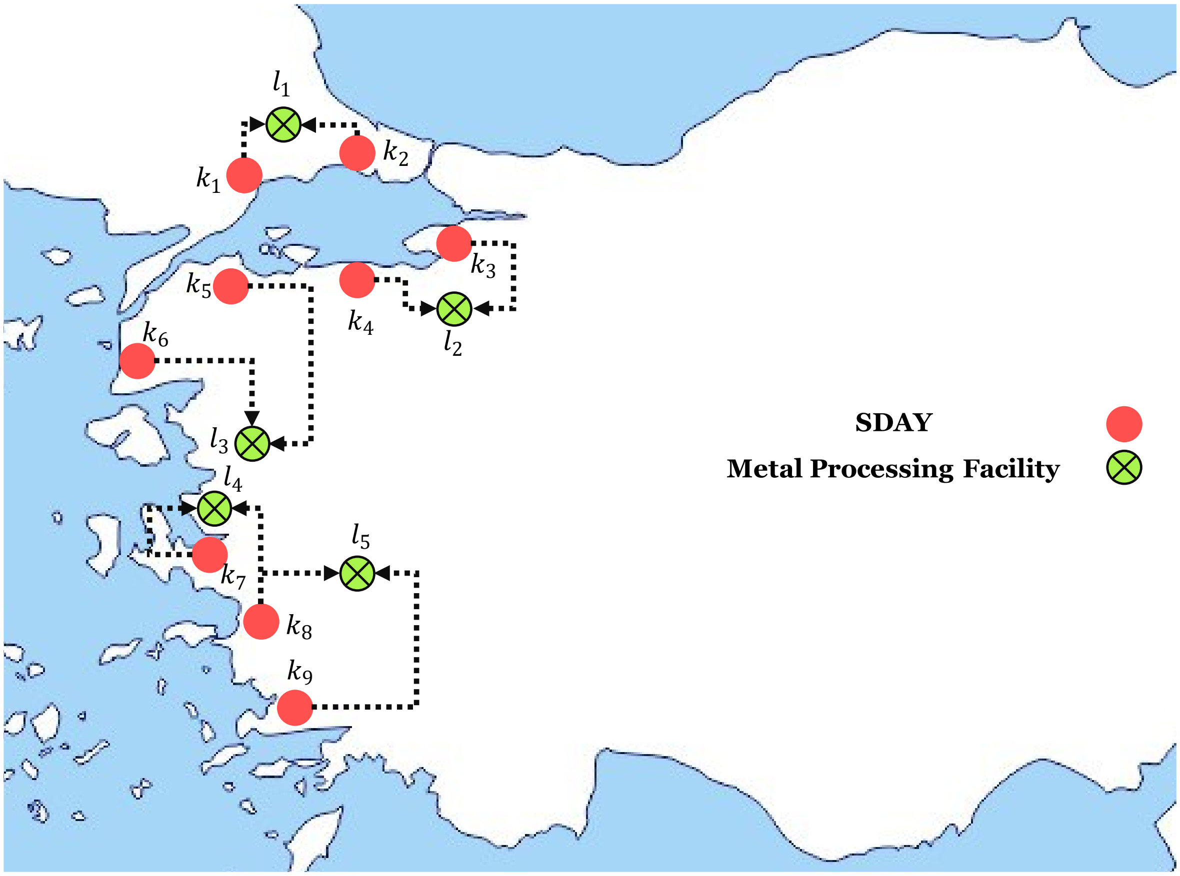


Figure 34. Optimal Flow of EoLSs from SDY to Metal Recycling Facility

Table 21. Number of Materials/Components between SDY and Metal Processing Facility

	Metal Processing Facility					
	SDY	l_1	l_2	l_3	l_4	l_5
B_{kl} (*ton*)	k_1	**45654**	–	–	–	–
	k_2	**34346**	–	–	–	–
	k_3	–	**45654**	–	–	–
	k_4	–	**34346**	–	–	–
	k_5	–	–	**31246**	–	–
	k_6	–	–	**48754**	–	–
	k_7	–	–	–	**49632**	–
	k_8	–	–	–	**18600**	**31400**
	k_9	–	–	–	–	**48600**

Given their heavy reliance on specific SDYs and processing facilities, stakeholders must ensure that these pivotal nodes are equipped with advanced technologies and best practices to enhance efficiency. Any operational hitches at these key points could ripple through the entire network, causing significant disruptions.

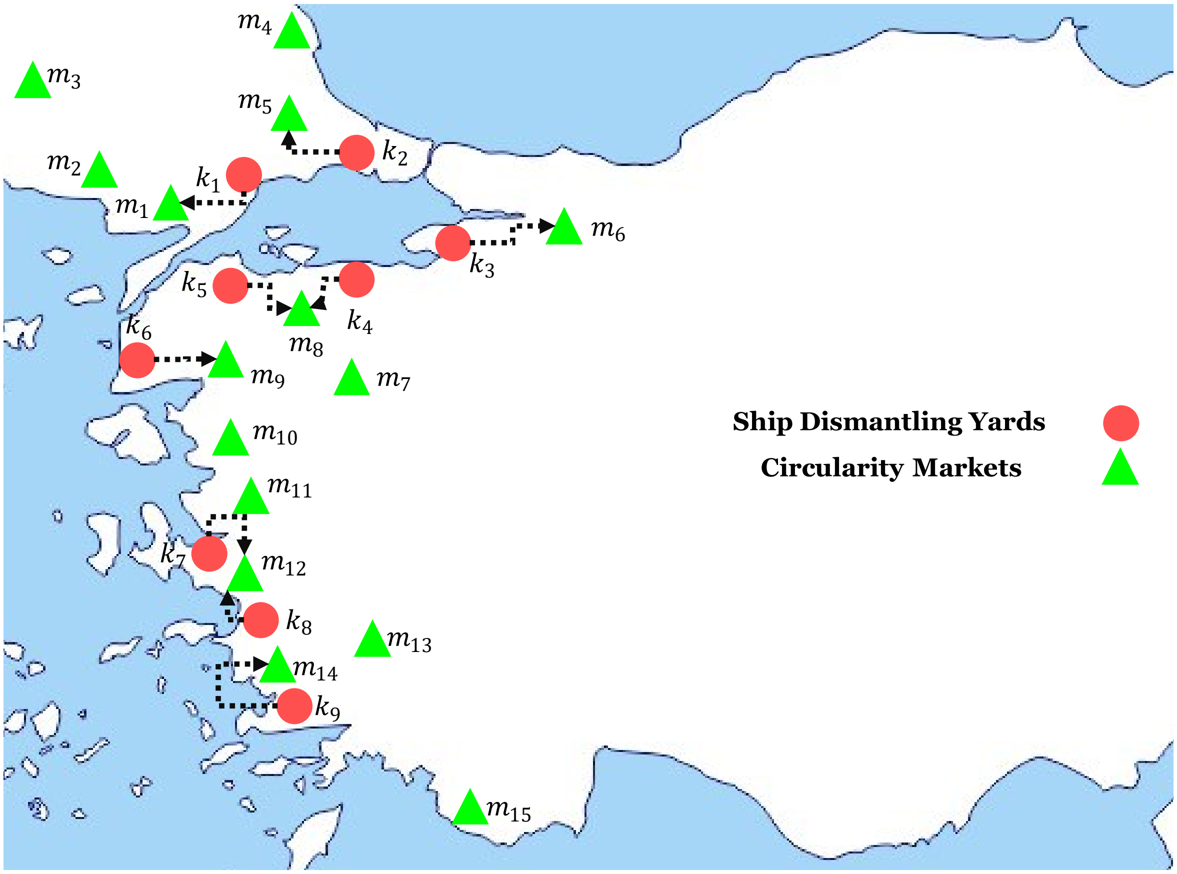


Figure 35. Optimal Flow of Usable Components from the SDYs to the Circularity Markets

Table 22. Number of Usable Components between SDYs and Circularity Markets

$S_{nkm}\ (ton)$, For Machinery Components	Circularity Market															
	SDYs	m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}	m_{11}	m_{12}	m_{13}	m_{14}	m_{15}
	k_1	**142.3**	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	k_2	—	—	—	—	**127.3**	—	—	—	—	—	—	—	—	—	—
	k_3	—	—	—	—	—	**142.6**	—	—	—	—	—	—	—	—	—
	k_4	—	—	—	—	—	—	—	**135.6**	—	—	—	—	—	—	—
	k_5	—	—	—	—	—	—	—	**131.8**	—	—	—	—	—	—	—
	k_6	—	—	—	—	—	—	—	—	**139.5**	—	—	—	—	—	—
	k_7	—	—	—	—	—	—	—	—	—	—	—	**127.4**	—	—	—
	k_8	—	—	—	—	—	—	—	—	—	—	—	**133.7**	—	—	—
	k_9	—	—	—	—	—	—	—	—	—	—	—	—	—	**144.6**	—

Figure 35 visually delineates the flow of usable components from SDYs to circularity markets, offering a clear illustration of the distribution network in the context of ship recycling. A complementary perspective is provided in Table 22, which quantifies the number of components transferred between two nodes. Moreover, the presence of multiple pathways leading from SDYs to various markets, as shown in Figure 35, underscores the flexibility and adaptability of this network, ensuring the sustainable and efficient reallocation of ship components. The implementation of such a strategy not only promotes the principles of a circular economy, but also potentially minimizes waste, maximizes the utility of EoL components, and potentially paves the way for significant economic benefits in the ship recycling industry.

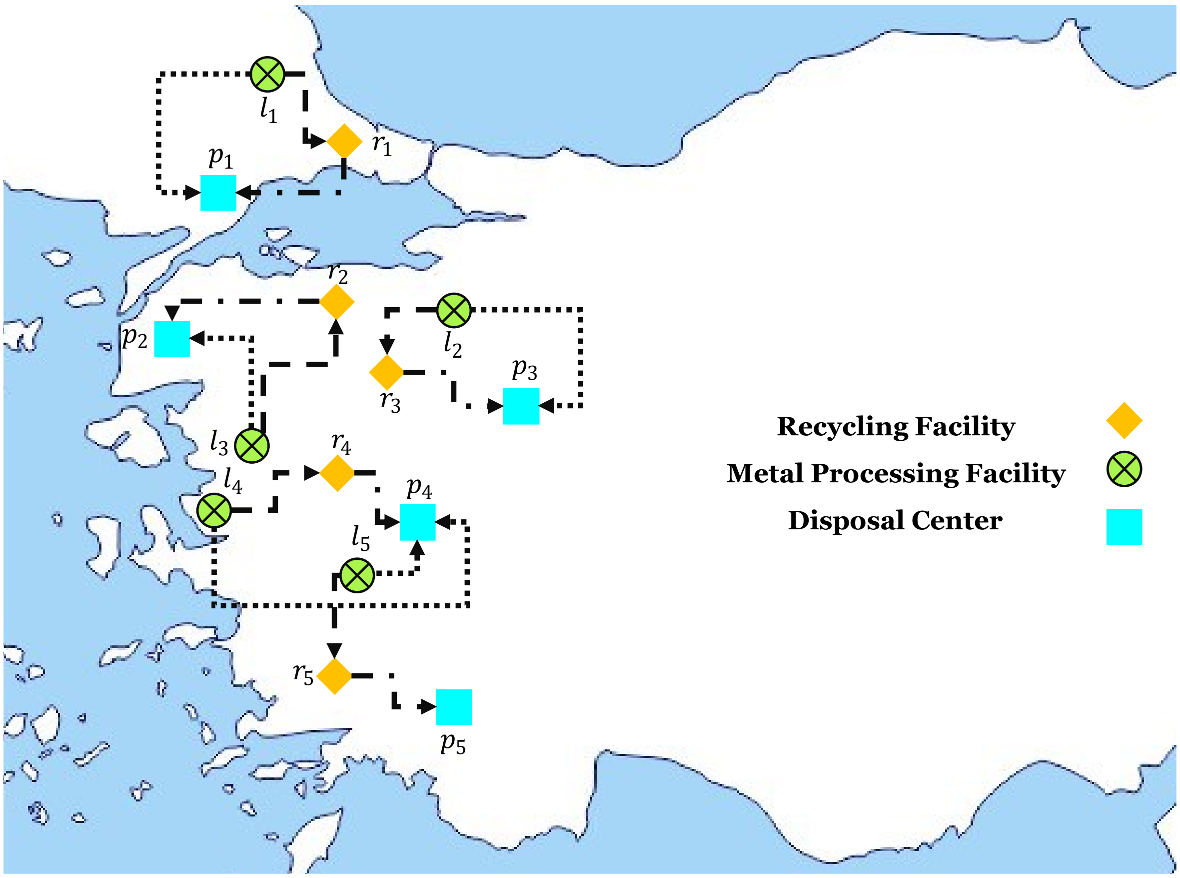


Figure 36. Optimal Flow of Materials from the MPF to RF and DC

Figure 36 illustrates the geographical dispersion and interconnectivity of metal processing facilities to recycling and disposal centers. Within this layout, clusters of three closely situated locations are evident, seemingly designed to optimize transportation routes and consequently reduce logistical expenses. Table 23 presents the quantitative aspects of these transfers. Table 24 focuses on the amount of SW transferred between the MPF and Disposal Centers, emphasizing the importance of disposal mechanisms in the recycling infrastructure. Additionally, Table 25 displays the amounts of hazardous materials that arise from the recycling processes and are subsequently transferred to disposal centers for appropriate handling and containment. Notably, ferrous metals contribute the most to hazardous materials, as they form 86% of the EoLS weight.

Table 23. Number of Materials transferred between the MPFs and RFs

G_{nlr} (ton)	Metal Facilities		r_1	r_2	r_3	r_4	r_5
	Ferrous Metal (n_6)	l_1	67693.32	—	—	—	—
		l_2	—	—	67506.15	—	—
		l_3	—	67641.3	—	—	—
		l_4	—	—	—	57654.9	—
		l_5	—	—	—	—	67701.3
	Non-Ferrous Metal (n_7)	l_1	1592.78	—	—	—	—
		l_2	—	—	1588.38	—	—
		l_3	—	1591.56	—	—	—
		l_4	—	—	—	1356.57	—
		l_5	—	—	—	—	1592.9

Table 24. Amount of SW Transferred between the MPFs and DCs

E_{lp} (ton)	Metal Facilities	p_1	p_2	p_3	p_4	p_5
	l_1	360.8	—	—	—	—
	l_2	—	—	581	—	—
	l_3	—	322	—	—	—
	l_4	—	—	—	402.7	—
	l_5	—	—	—	351.4	—

Table 25. Number of Hazardous Materials Resulted from RFs Sent to DCs

F_{nrp} (ton)	Recycling Facilities	Disposal Centers	Plastic (n_1)	Glass (n_2)	Fluids (n_3)	Minerals (n_4)	Joinery (n_5)	Ferrous Metal (n_6)	Non-Ferrous Metal (n_7)
	r_1	p_1	0.7	0.3	4.3	1.3	0.3	3046.2	65.7
	r_2	p_2	0.7	0.6	4.3	1.6	0.4	3043.8	64.6
	r_3	p_3	0.8	0.4	4.3	1.2	0.6	3037.8	63.5
	r_4	p_4	0.7	0.5	5.6	1.2	0.4	2594.4	61.1
	r_5	p_5	0.6	0.5	5.5	1.5	0.5	3046.6	63.7

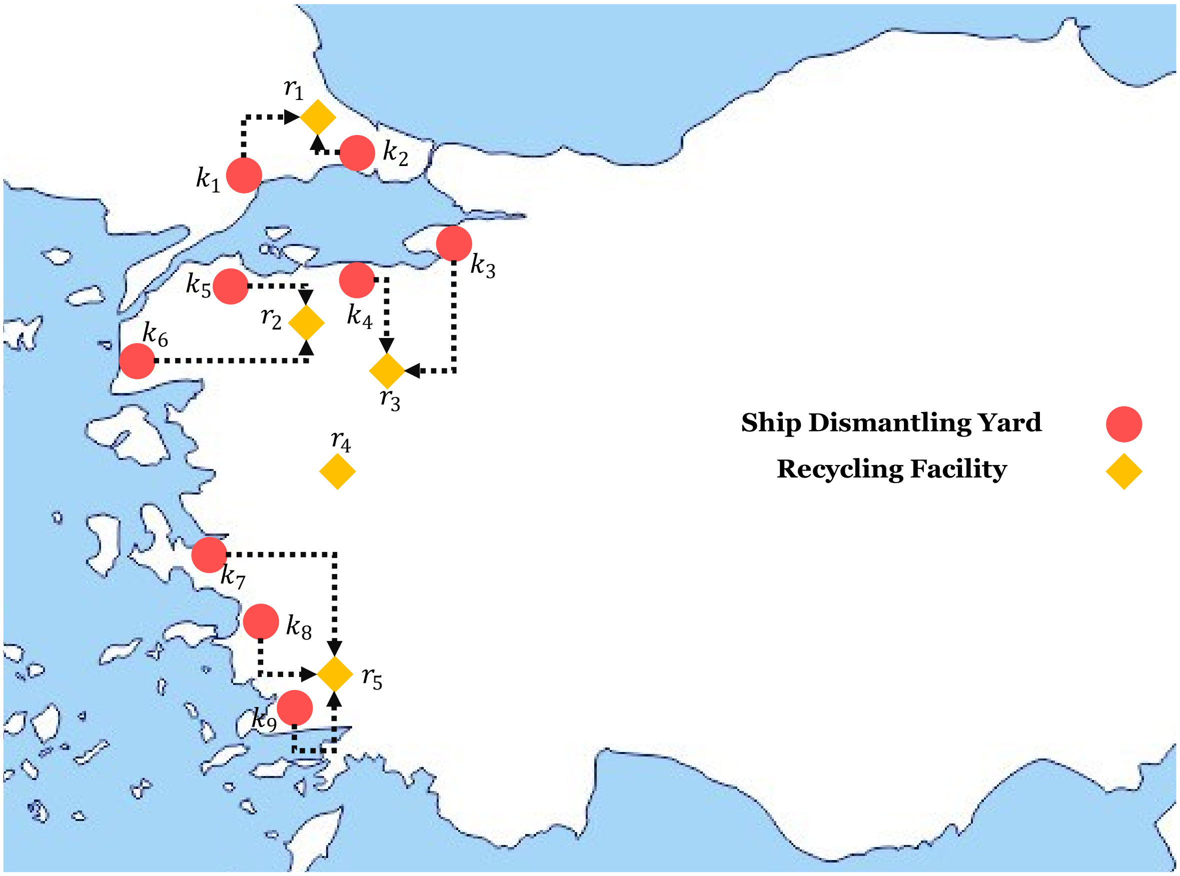


Figure 37. Optimal Flow of Materials from the SDYs to Recycling Facilities

Table 26. Number of Recyclable Components Transferred between the SDYs and RFs

	SDYs	Recycling Facilities	Recycled Components and Materials				
			Plastic (n_1)	Glass (n_2)	Fluids (n_3)	Minerals (n_4)	Joinery (n_5)
A_{nkr} (ton)	k_1	r_1	113.4	13.1	17.8	21.1	11.7
	k_2		115.2	11.5	15.3	19.8	10.3
	k_5	r_2	120.2	11.2	13.8	16.4	15.1
	k_6		93.6	15.4	11.7	22.8	12.8
	k_3	r_3	122.1	12.6	16.1	15.7	12.4
	k_4		110.9	14.2	14.4	23.1	13.1
	k_7	r_5	107.3	11.2	14.6	13.2	11.4
	k_8		121.8	13.6	14.8	13.2	12.6
	k_9		111.4	10.6	11.3	12.5	11.7

Figure 37 shows a spatial representation of the flow of materials from SDYs to recycling facilities. Table 26 quantifies the movement of recyclable components, offering a detailed breakdown of the material transfers. Figure 38 shows the flow of recycled materials from the recycling facilities to circularity markets, illuminating a web of connections across the region. The distribution of circularity markets, represented by green triangles, is widespread, reflecting extensive market reach and potential demand for recycled materials. Table 27 lists the quantities of materials sold in the markets. The depicted flow of recycled materials from recycling facilities to circularity markets epitomizes the essence of resource optimization and waste minimization that the circular economy promotes. By redistributing salvaged materials to various circularity markets, the ship recycling industry not only ensures the sustainable reuse of valuable resources, but also fosters an ecosystem of interdependent markets.

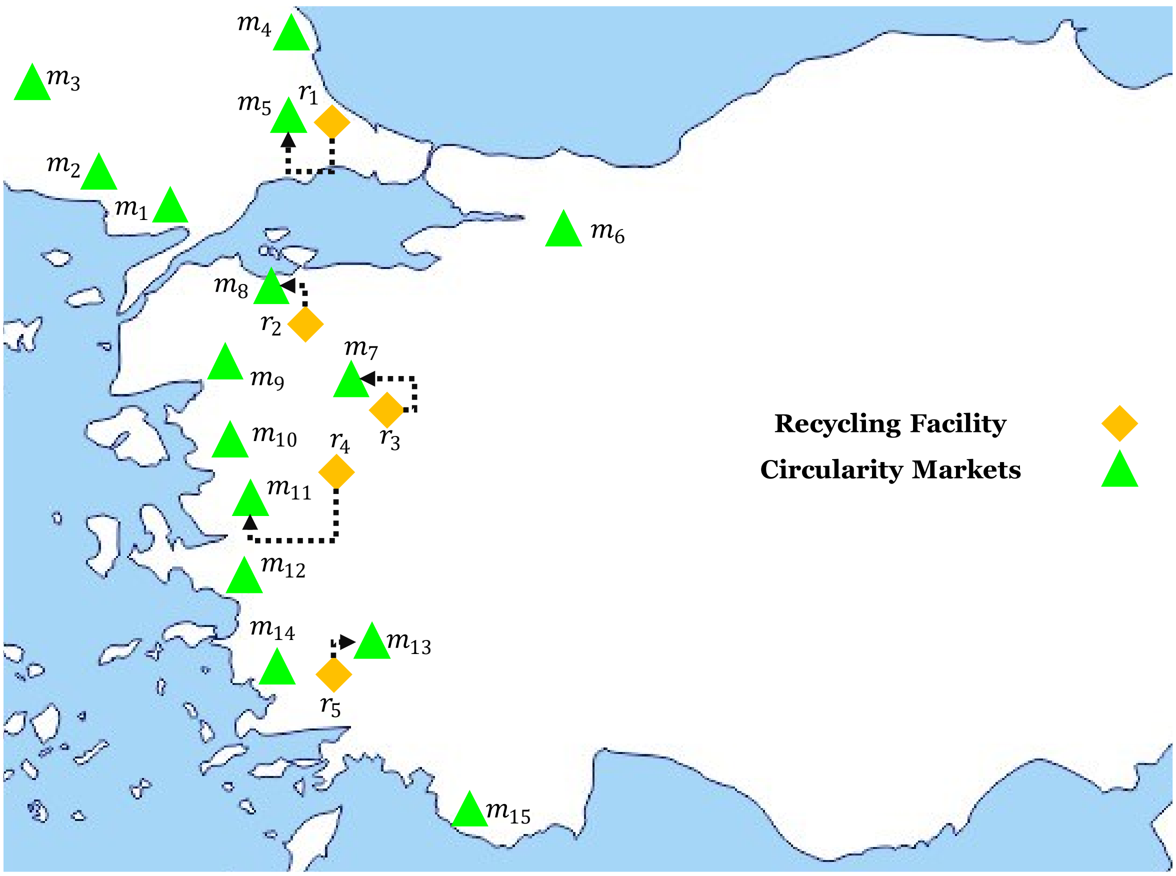


Figure 38. Optimal Flow of Recycled Materials from Recycling Facilities to Circularity Markets

Table 27. Recycled Materials Sold in the Circularity Markets

FM_{nrm} (ton)	Recycling Facilities	Markets	Recycled Components and Materials						
			Plastic (n_1)	Glass (n_2)	Fluids (n_3)	Minerals (n_4)	Joinery (n_5)	Ferrous Metal (n_6)	Non-Ferrous Metal (n_7)
	r_1	m_5	12.2	11.3	14.3	5.3	3.3	1686	975
	r_2	m_8	11.3	11.3	14.3	5.3	4.6	1668	927
	r_3	m_7	12.1	14.5	14.3	5.3	2.4	1668	975
	r_4	m_{11}	12.1	14.5	11.6	5.2	2.2	1668	975
	r_5	m_{13}	11.6	14.5	11.3	5.3	4.5	1795	975

4.2 Economic Assessment

The economic assessment of CLSCN in the ship recycling industry is a pivotal aspect of this study, offering a critical lens through which we can evaluate the financial feasibility and viability of sustainable practices within this dynamic sector. In a world increasingly focused on environmental responsibility and resource conservation, it is imperative to not only consider the ecological implications of recycling ships, but also to scrutinize the economic dimensions of such operations. This section provides an in-depth exploration of the economic intricacies associated with closed-loop supply chains in ship recycling, with an emphasis on cost structures, revenue models, investment considerations, and potential financial benefits. By systematically dissecting the economic aspects of this industry, we aim to provide valuable insights for industry stakeholders and policymakers, fostering a deeper understanding of the economic viability of sustainable practices in ship recycling, and contributing to the ongoing discourse on sustainable business strategies within this vital domain.

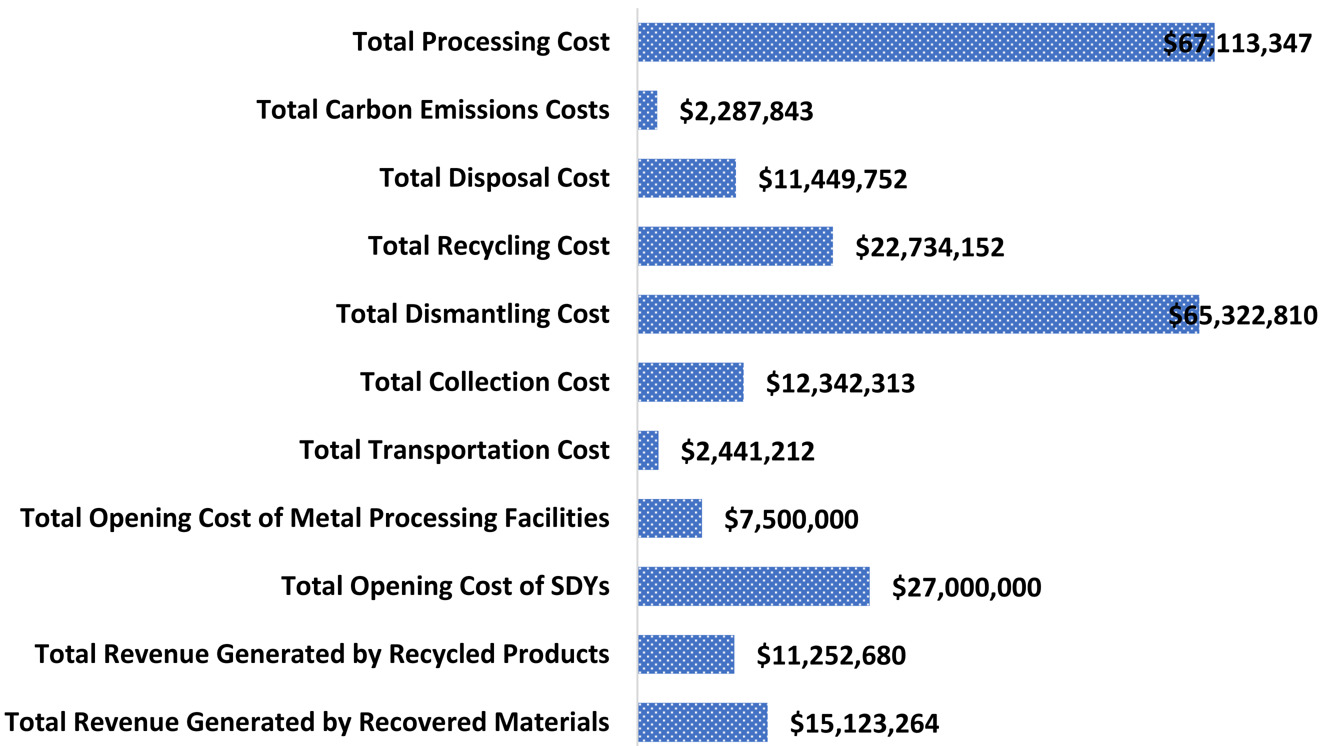


Figure 39. Breakdown of the Cost Function into its Main Components

The total value of the cost function is $ 191,815,485. Figure 39 provides a detailed breakdown of the costs involved in the ship recycling industry, alongside the revenues generated from the circularity of materials. The primary financial burden emerges from the dismantling process, which commands a cost of $65,322,810, highlighting the significant labor and resources dedicated to this initial stage. Processing costs follow closely, tallying up to $67,113,347, reflecting the substantial expenses involved in transforming salvaged materials for reuse. Recycling and disposal also represent notable costs, at $22,734,152 and $11,449,752 respectively, underlining the critical investments required for managing the lifecycle of materials beyond dismantling. Operational costs for collection and transportation are $12,342,313 and $2,441,212, respectively, illustrating the importance of logistics in connecting the various nodes of the CLSCN. The initial expenditures for establishing metal processing facilities and Ship Dismantling Yards (SDYs) stand at $7,500,000 and $27,000,000, laying the financial foundation for the network's infrastructure. On the revenue side, the sale of recycled products yields $11,252,680, while the revenue from recovered materials is $15,123,264. These figures attest to the financial viability of material recovery and recycling, with the latter contributing a greater share to the overall income. This supports the premise that not only do recycling, and recovery align with environmental objectives, but they also hold considerable economic potential.

The industry's focus on efficiency and cost reduction—particularly in the high-cost arenas of dismantling and processing—can lead to enhanced profitability. While transportation costs are contained, suggesting an already streamlined logistics system, the potential for further optimization persists. Maximizing the returns from circularity market sales is crucial; the collective revenues from recycled and recovered materials underscore the substantial value encapsulated within the circular economy. Thus, as the sector stands at the confluence of environmental responsibility and economic performance, these insights delineate a strategic path toward cost efficiency and operational excellence in the pursuit of sustainable ship recycling.

4.3 Environmental Assessment

In today's globalized world, the ship recycling industry plays a pivotal role in managing the EoL ships. As the demand for sustainable practices and environmental responsibility continues to grow, it is imperative to scrutinize the processes within this industry through an environmental assessment lens. CLSCN in ship recycling holds the promise of not only efficiently recovering valuable materials and components but also mitigating the adverse environmental impacts traditionally associated with ship dismantling and disposal. This section explores the multifaceted environmental considerations inherent to ship recycling operations. It delves into the environmental assessment of various stages within the closed-loop supply chain, shedding light on the challenges and opportunities that arise. By examining the environmental implications, evaluating eco-efficiency, and proposing strategies for sustainable ship recycling, this research endeavors to contribute to the transformation of the ship recycling industry into an environmentally responsible and economically viable sector, aligned with the principles of a circular economy.

The pie chart (Figure 40) illustrates the CO_2 emissions produced within the network. It is evident that metal processing is the most substantial contributor, accounting for 41% of the total emissions. This significant percentage underscores the environmental costs associated with the energy-demanding activities of metal refining and processing. Implementing energy-saving smelting technologies and reclaiming waste heat could diminish this impact. The process of dismantling ships follows, representing 29% of emissions, which stems from the labor and energy-intensive nature of breaking down ships. The adoption of innovative robotics and more precise dismantling methods could mitigate these emissions, as could the utilization of ship components that can be reused with minimal processing, as suggested in this thesis.

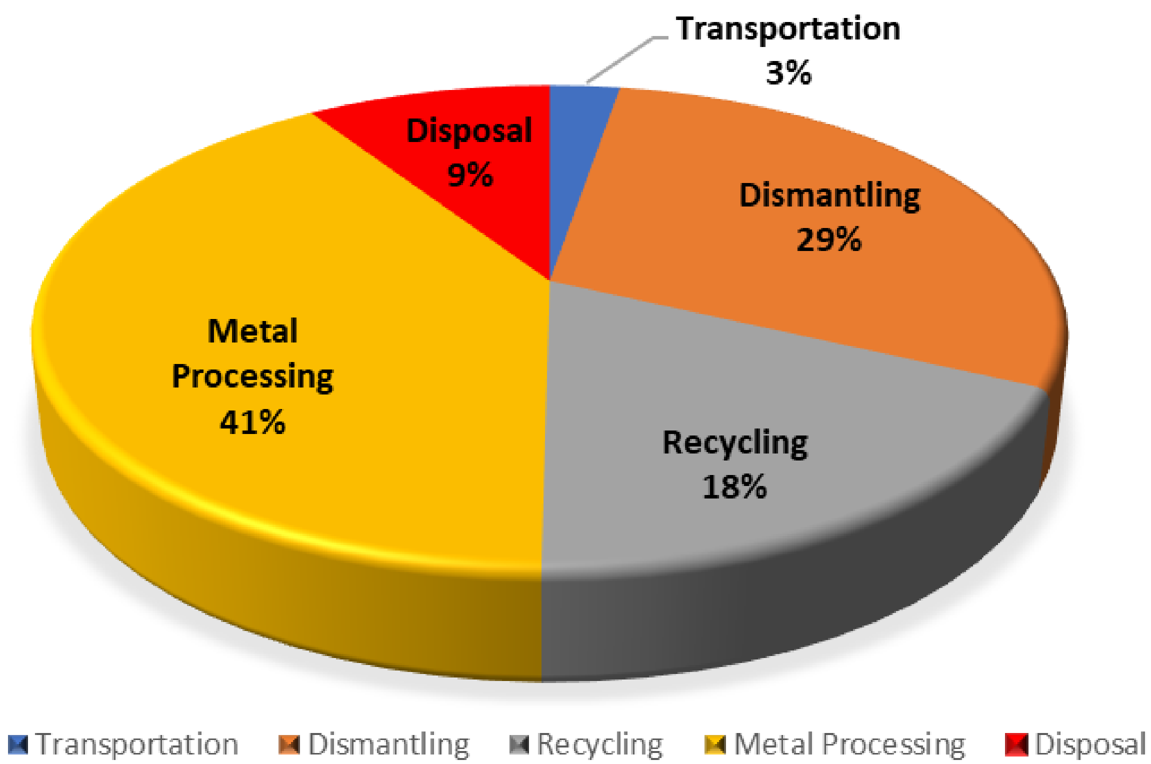


Figure 40. Network Carbon Emissions Breakdown

Recycling processes contribute to 18% of the emissions, a figure that, while lower than metal processing, still indicates the environmental cost of repurposing ship materials. Innovations in recycling technology and the integration of renewable energy sources for powering these operations could reduce this footprint. The assembly phase, which involves the utilization of heavy machinery, corresponds to a lower proportion of emissions not depicted in this chart, highlighting the opportunity for increased efficiency through energy-efficient machinery and optimized assembly practices.

Disposal activities, although they make up 9% of emissions, still represent a critical area for potential improvements. Enhanced segregation and redirection of materials could decrease the volume of waste, while waste-to-energy initiatives could transform non-recyclable materials into a beneficial resource. Meanwhile, transportation is responsible for the smallest share of emissions at 3%, suggesting it is already relatively efficient but could still benefit from optimization strategies, such as route planning and the use of low-emission vehicles. Collectively, these insights inform strategies for emissions reduction across the network, reinforcing the need for innovation and efficiency at every stage.

4.4 Sensitivity Analysis

Understanding the sensitivity of key variables within a closed-loop supply chain network is of paramount importance in the complex and dynamic landscape of the ship recycling industry. This section presents a comprehensive sensitivity analysis that aims to uncover the intricate interplay between various factors influencing the design and operation of the CLSCN in ship recycling. By systematically examining the impact of fluctuations in these variables, we seek to provide valuable insights that can guide decision makers, policymakers, and industry stakeholders toward more robust and resilient closed-loop supply chain strategies. Through this exploration, we aim to shed light on how changes in critical parameters can affect the efficiency, environmental impact, and overall sustainability of ship recycling operations, ultimately contributing to the ongoing discourse on sustainable practices in this vital industry.

Sensitivity analysis (Figure 41) was performed to determine the optimal network cost. The parameters that are most vulnerable to market fluctuations, including the cost of technology-related capital expenditures and fuel prices, are considered. Furthermore, the costs related to dismantling, collection, and recycling were examined. All these parameters were adjusted by a decrease or increase of 20% from their foundational values to study their effects. The initial values are listed in Table 11.

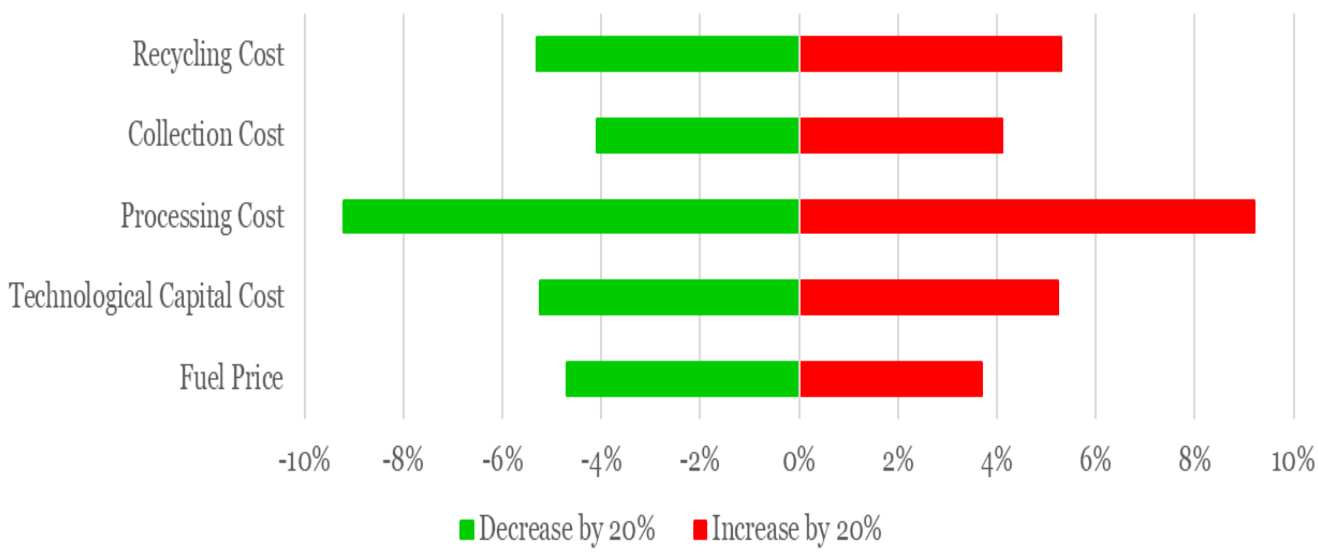


Figure 41. Sensitivity Analysis on The Optimal Network's Cost

The sensitivity analysis conducted within the ship recycling industry framework highlights the significant relationships between various cost factors and their collective impact on the total cost. Processing costs are shown to be extremely sensitive; a 20% increase in processing costs correlates with a 9.20% rise in total costs. This underscores the substantial influence of processing efficiency on the industry's financial health. Similarly, technological capital costs play a pivotal role. A reduction of 20% in these costs can lead to a corresponding decrease in overall costs by 5.23%, emphasizing the leverage that investment in technology wields over cost optimization.

The analysis also shows that recycling costs are critical, with a 20% fluctuation in recycling expenses affecting total costs by 5.30%. Collection costs, while exhibiting a smaller impact relative to processing and recycling, still contribute a 4.10% change with a 20% cost variation, underlining their significance in cost management strategies. Fuel prices, often a variable and unpredictable factor, also have a notable effect; a 20% change in fuel prices leads to a 4.70% alteration in total costs. This demonstrates the importance of monitoring fuel prices due to their direct connection to transportation expenses. In aggregate, the analysis accentuates the need for meticulous cost control across all operational domains, particularly in processing, technology adoption, and recycling efforts. By pinpointing the most impactful areas for cost reduction, the ship recycling industry can strategically target improvements to enhance financial performance and sustainability.

Figure 42 describes a detailed sensitivity analysis that evaluates the impact of various operational parameters on the total carbon emissions within a ship recycling network. The analysis reveals that metal processing exerts the most considerable influence: a 20% reduction in emissions from metal processing corresponds to a significant decrease of 9.28% in the network's overall emissions. On the other hand, a 20% increase in metal processing emissions incurs a comparable rise in the network's total emissions by the same percentage. Dismantling activities also significantly impact carbon emissions, with a 4.84% shift in the network's total emissions resulting from a 20% adjustment in dismantling emissions. Recycling follows suit, with a 3.01% change in network emissions when recycling emissions fluctuate by 20%.

Transportation shows a notable sensitivity, where a 20% variation in emissions translates to a 3.35% change in the network's total emissions. Disposal processes, though less impactful than metal processing and dismantling, still influence the network's carbon footprint with a 2.60% change when disposal emissions are increased or decreased by 20%. This sensitivity analysis underscores the interconnectedness of the operational processes and their collective influence on the carbon emissions of the ship recycling network. It highlights the areas where modifications in operational practices could lead to substantial improvements in environmental performance.

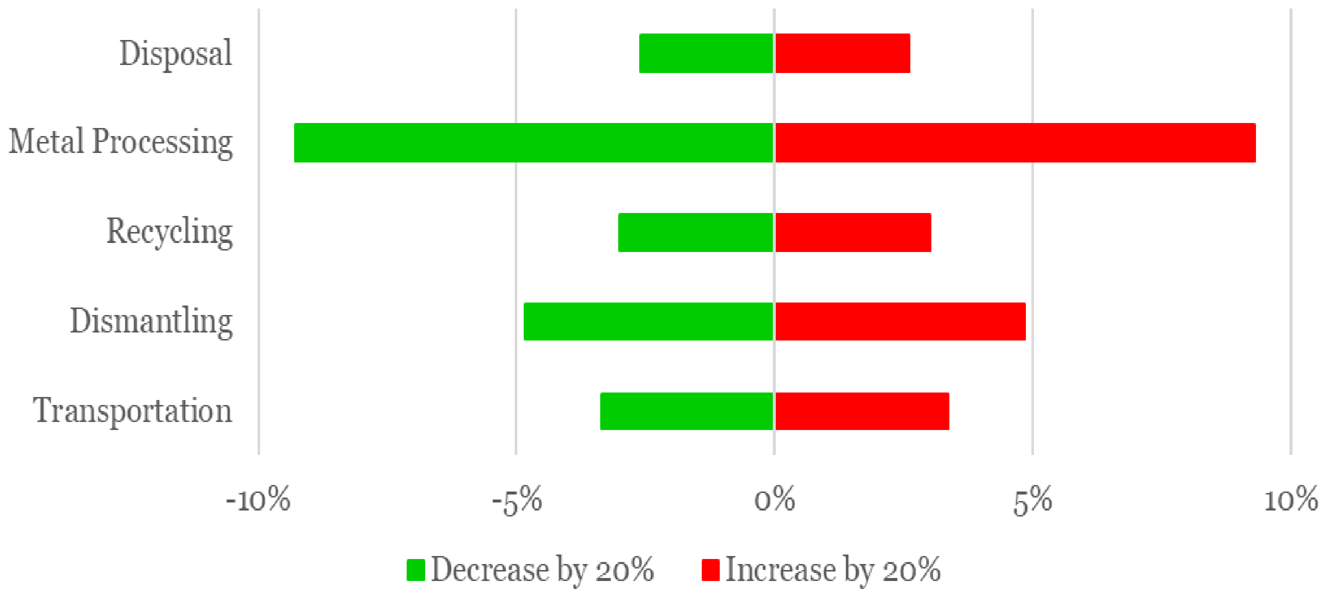


Figure 42. Sensitivity Analysis on The Network's Carbon Emissions

4.5 Computational Complexity

In this section, we discuss the intricacies involved in solving the optimization problem. The problem formulation was programmed in Python, a versatile high-level programming language known for its efficacy in handling complex data structures and computations. For the solution process, we utilized the Gurobi optimizer, renowned for its advanced algorithms and performance efficiency, on an Intel(R) Core i7-2600 CPU with a clock speed of 3.40 GHz. This computational setup was tasked with navigating through a solution space defined by 1,621 decision variables. Despite the considerable number of variables, which typically signifies a challenging computational task, the Gurobi optimizer, coupled with the processing power of the CPU, achieved a solution in approximately 15 minutes. This performance is indicative of both the sophisticated optimization capabilities of the software and the computational power of modern processors. The Python code can be found in Appendix One.

4.6 Pareto Optimality

In the domain of ship recycling, the concept of Pareto optimality within the CLSCN is pivotal for achieving an equilibrium where no stakeholder's position can be improved without worsening another's. This principle is particularly significant in balancing the economic, environmental, and social objectives intrinsic to the ship recycling process. A Pareto optimal solution in a CLSCN is one where the cost efficiency, resource utilization, and environmental impact are optimized to a point where any further improvement in one aspect would lead to a trade-off in another(He et al., 2014; Zhang et al., 2022). For instance, reducing costs further may result in higher emissions or lower safety standards, which is undesirable. The challenge lies in identifying the set of Pareto efficient solutions that represent the best possible trade-offs among conflicting objectives, such as minimizing costs while maximizing material recovery and minimizing carbon footprint(Zhang et al., 2022). This involves using multi-objective optimization techniques that can navigate the complex landscape of ship recycling operations, considering the diverse and sometimes competing interests of various stakeholders, from ship owners to environmental agencies. Achieving Pareto Optimality ensures that the CLSCN operates in a manner that is not only sustainable and profitable but also equitable and responsible.

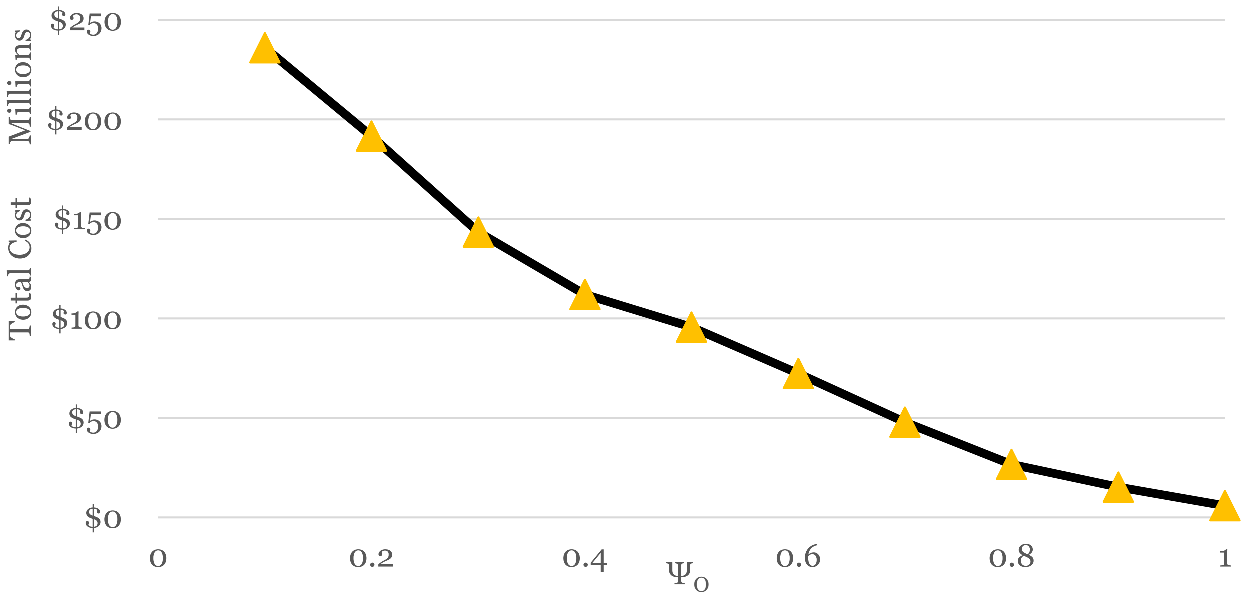


Figure 43. Pareto Frontier between Total Cost and Ψ_0

Figure 43 offers a compelling visualization of the relationship between the total cost and the weight given to the total operational cost (Ψ_0), in the context of ship recycling operations. The depicted trend indicates that as greater importance is placed on the operational cost, the associated costs decrease which also affect the total cost. This observation suggests that prioritizing operational sustainability, specifically the cost savings strategies, can lead to lower overall costs. Such a correlation provides robust support for integrating sustainable practices within operational frameworks, reinforcing the argument that environmental consciousness and cost savings can go hand in hand.

Moreover, the pursuit of operational cost reductions often leads to economies of scale. When recycling operations are scaled up, the average cost of processing materials decreases due to bulk procurement and more efficient handling of larger volumes. This scale can extend the cost benefits across the network, reducing the total cost per unit of output. Attention to operational costs also entails a rigorous approach to waste reduction. Precise separation techniques yield higher-quality recycled materials, thereby fetching better market prices. In a closed loop system, the reuse of parts and components can further drive down the cost of sourcing new materials, aligning with sustainable practices while enhancing profitability. Optimization of the supply chain is another critical area where focusing on operational costs pays dividends. This involves fine-tuning logistics to ensure efficient transport to recycling facilities, managing inventories in line with market demands, and creating a more robust and responsive sales strategy for the output materials. Such optimization not only reduces costs but also improves the agility of the supply chain to respond to market fluctuations.

The standardization of procedures across recycling operations ensures consistency and the adherence to best practices. This reduces the likelihood of errors and rework, which are cost-inducing, and ensures compliance with environmental standards, potentially avoiding hefty fines and reputational damage. Effective management of resources, particularly in terms of energy and water use, is also crucial. Employing energy-efficient machinery and recycling process water can lead to substantial reductions in utility costs. These savings are particularly significant in the heavy-industry context of ship recycling. Lastly, investment in labor management and training plays a substantial role in operational cost reduction. A well-trained workforce operates more efficiently, reducing the incidence of costly errors and increasing productivity. Efficient scheduling and management of labor forces ensure that operations are lean and cost-effective.

Table 28. Pareto Frontier Data

Ψ_O	TEC	TOC
0.1	$778,242	$236,054,546
0.2	$928,242	$191,585,148
0.3	$1,228,242	$143,040,749
0.4	$1,467,342	$111,460,711
0.5	$1,653,229	$94,859,459
0.6	$1,892,142	$71,189,214
0.7	$2,125,242	$46,475,255
0.8	` $2,425,272	$24,661,133
0.9	$2,721,242	$12,790,658
1	$2,921,272	$2,956,930

However, the graph also raises questions about the underlying data's veracity. If the results are unexpected or seem counterintuitive—typically, one might assume that prioritizing carbon emissions reduction could increase total costs—then it might indicate that the operational or carbon emission cost estimates could be unrealistic. This discrepancy could stem from overly optimistic projections for the financial benefits of reducing emissions or from underestimating the costs associated with operational changes. Given the potential for these contrasting interpretations, the conclusions drawn from this analysis should be approached with caution. While the data may strongly support a move towards sustainability as a cost-effective strategy, it could also point to a need for a more nuanced and realistic appraisal of the costs involved. Therefore, it is prudent to recommend that this area be subjected to further detailed research. Future studies could focus on validating the cost models used for operations and carbon emissions, thereby ensuring that strategic decisions are made based on reliable and accurate financial implications.

Figure 44 illustrates the trade-off between TEC and TOC, both measured in millions of dollars. The data points on the graph correspond to the values provided in table 28. We observe a clear negative correlation between TOC and TEC. This suggest that operations which are more cost-intensive tend to be associated with lower emissions costs. This implies that investing in more expensive and efficient recycling processes or technologies lead to a decrease in emissions, due to more comprehensive waste management and efficient material processing that reduces environmental impact. For the ship recycling industry, this analysis indicates a strategic decision point: investing heavily in operations yield a more environmentally friendly process, but the cost of achieving the lowest possible emissions may not always be justified by the incremental environmental benefits gained. This necessitates a balanced approach where both economic and environmental sustainability are optimized.

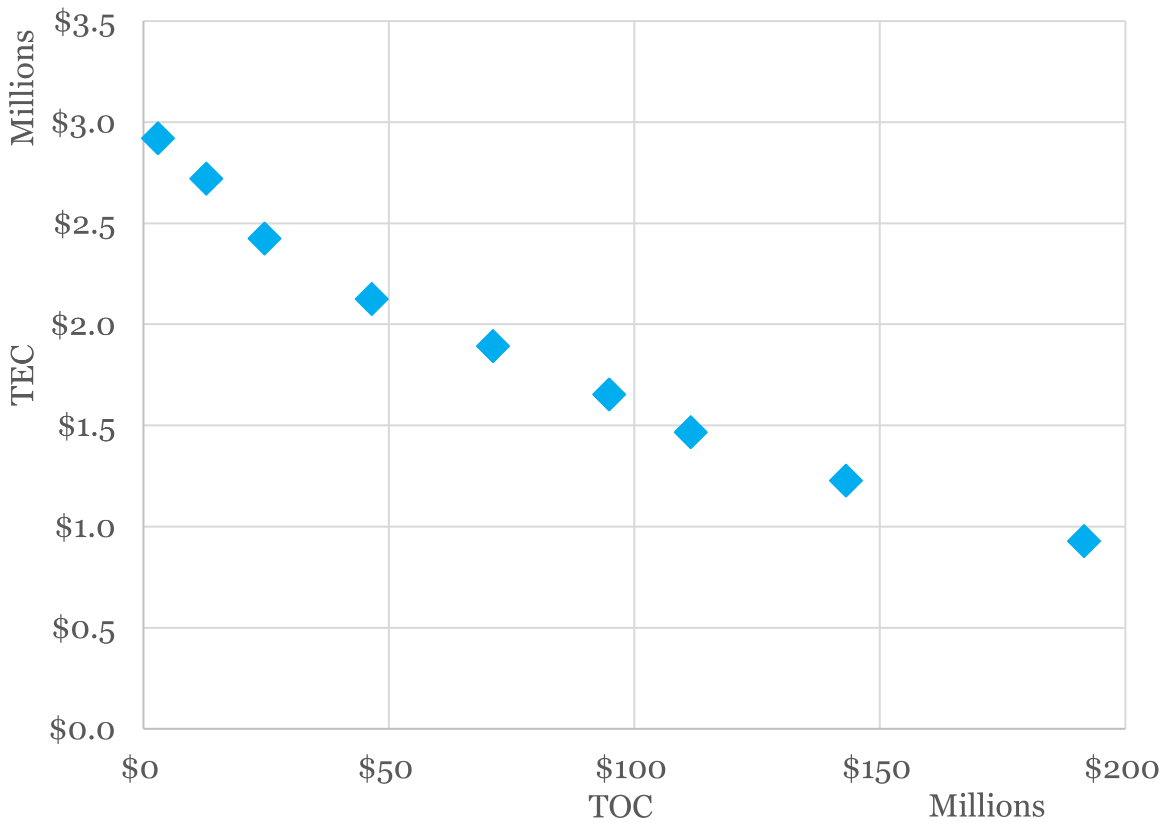


Figure 44. Pareto Efficiency Frontier for TEC and TOC

Incorporating the insights gleaned from the Pareto Efficiency Frontier, this thesis advocates for the creation of a strategic decision-making framework within the CLSCN for ship recycling. This framework is instrumental in pinpointing the most economically prudent investment junctures. It aids in orchestrating an optimal resource allocation that concurrently minimizes emissions and operational costs, propelling the ship recycling industry towards a greener horizon. This methodology transcends mere environmental considerations, grappling with the economic exigencies of ship recycling operations to ensure that the strides towards sustainability are firmly rooted in commercial feasibility.

4.7 Insights and Implications

Considering the increasing prominence of the circular economy, growing influence of regulatory requirements, and heightened awareness of environmental concerns, it is imperative for shipping enterprises to explore the potential adoption of a remanufacturing strategy. This strategic approach holds the promise of significantly reducing environmental waste, facilitating the recycling of discarded metals, and enabling the restoration and reutilization of components from retired shipping vessels. It can be argued that ship recycling serves as an effective intervention not only to mitigate the risk of ecosystem degradation but also to create employment opportunities under the protection of robust labor laws. This ensures the preservation of fundamental rights and provision of equitable wages for workers operating in demanding conditions. This widespread consensus supports the assertion that remanufacturing plays a pivotal role in the successful transition toward a circular economy, enabling a change in thinking in supply chains from linear to closed-loop models. Nevertheless, the market-based evaluation of the cost-effectiveness of EoL ship recycling has certain limitations. This assessment must encompass factors such as potential revenue influenced by pricing and volume, savings accrued from social and environmental costs, and competition stemming from ship-leasing activities.

The findings from this research offer a wealth of managerial insights that can be utilized to improve the structure of a CLSCN by addressing the intricacies involved in the remanufacturing of EoL ships. The framework presented here offers managers a solid mathematical tool that can be adjusted slightly and applied to any reverse logistics network under the EoLS paradigm. Managers have the flexibility to choose between deterministic and stochastic versions of the model depending on the certainty of their parameters. From a public policy standpoint, the significance of ship recycling extends beyond geographical or national borders. Therefore, it is imperative to adopt a collective and collaborative responsibility model to promote the recycling or remanufacturing of EoL ships in economically efficient locations, where the advantages of the shipping industry often go unnoticed. Meanwhile, the adverse environmental consequences and substandard labor conditions prevalent in the shipwrecking sector are the most pronounced. Hence, there is an urgent need for public policy discourse aimed at determining the suitable funding mechanisms and financial tools necessary to bolster ship recycling initiatives. This debate is crucial to ensure that the environmental and social benefits associated with ship recycling are realized in a manner that transcends national boundaries and promotes sustainability on a global scale.

4.8 Chapter Summary

This chapter unfolds with an in-depth **Optimal Network Design** analysis, delineating the model's configurations to enhance material and information flow efficiencies within the ship recycling industry's CLSCN. It progresses to an **Economic Assessment**, scrutinizing the financial underpinnings and identifying processing costs as pivotal, with discussions around cost reduction through automation and efficient methodologies. The chapter then navigates through an **Environmental Assessment**, where it assesses the network's ecological footprint, particularly emphasizing CO_2 emissions and the environmental demands of metal processing, and advocates for the adoption of greener technologies. In the **Sensitivity Analysis**, the discussion pivots to the significant impact of processing and assembly costs, marking them as crucial levers in steering the network towards economic and environmental optimization.

Moving deeper into the network's operational intricacies, the **Computational Complexity** section contemplates the computational challenges inherent in optimizing the CLSCN, while the **Pareto Optimality** section reflects on the equilibrium attained between divergent sustainability goals, shedding light on multi-criteria optimization. The chapter culminates with **Insights and Implications**, adopting a prescriptive stance that champions remanufacturing strategies and global cooperation in ship recycling. This conclusive section advocates for policy innovation and financial initiatives to bolster sustainable practices, weaving together the interdependencies of economic viability, environmental responsibility, and policy frameworks. Overall, the chapter does not merely catalog findings; it offers actionable insights, advocating a comprehensive approach to ship recycling that transcends operational boundaries and promotes a collaborative international ethos.

To conclude, this chapter does not merely rest on a descriptive analysis; it takes a prescriptive turn, proffering insights and implications that hold profound ramifications for the industry. The merits of remanufacturing strategies are extolled, not just for their economic incentives but also for their potential in environmental waste mitigation and ship component restoration. The advocacy for a holistic, global approach to ship recycling resonates through the chapter, making a compelling case for transcending nationalistic barriers and fostering a spirit of collaborative responsibility. In its final strokes, this chapter provides the reader with invaluable managerial insights, championing a mathematical framework for reverse logistics in ship recycling. Clarion calls for a policy discourse aimed at fortifying ship recycling initiatives, especially through novel funding mechanisms, is a fitting endnote, emphasizing the symbiosis of economics, the environment, and policy in this intricate domain.

Chapter 5: Conclusion

The ship recycling industry, an integral part of the maritime sector, has long faced the dual challenges of environmental sustainability and economic viability. Historically, industry practices have often been criticized for their adverse impacts on the environment, safety concerns, and inefficient resource utilization. However, in an era characterized by a heightened awareness of environmental responsibilities and the circular economy ethos, the ship recycling industry is at a pivotal crossroads. This master's thesis embarked on a journey to chart a new course for the industry through the development and exploration of the CLSCN, a transformative concept with the potential to redefine ship recycling. By examining the results and analyzing the implications of the research, this section aims to provide a comprehensive summary of the study's key contributions and outcomes. It highlights the achievements and limitations of the research, as well as the implications for theory, practice, and future research in the field of the circular economy. The conclusion also offers recommendations for policymakers, industry stakeholders, and practitioners on how to advance and promote circular economy practices in the industry. Ultimately, this section serves as a closing statement, encapsulating the significance and potential of integrating circular economy principles into the ship recycling sector and emphasizing the importance of sustainable and resource-efficient practices in a global context.

5.1 Summary of The Findings

Ship recycling offers substantial advantages for customers, businesses, the environment, and society. Arguably, it can serve as a proactive measure to mitigate the risks associated with the degradation of fragile ecosystems, while concurrently generating employment opportunities under labor laws that safeguard basic rights and ensure fair wages for vulnerable workers operating in challenging conditions. The transition to ship recycling represents a significant value-enhancing strategy to bolster the sustainability of the shipbuilding industry. The model and solution methodology developed in this study for designing an efficient CLSCN can be applied to other locations to assess the feasibility of EoLS remanufacturing. However, it is essential to acknowledge that the absence of real-world data was a limitation of this study. Future research endeavors should strive to incorporate real data to improve the accuracy of the model results. Additionally, this study focused exclusively on general bulk carrier ships, but future research could explore the design of a multi-product, multi-objective mixed-integer linear programming system that combines total cost minimization with carbon emission minimization.

In the previous chapter, a sophisticated optimal network design that seamlessly merges both forward and reverse logistics was presented. Several pivotal facilities are at the heart of this network. These include metal processing plants, suppliers, circularity markets, recycling facilities, and disposal centers. Venturing the financial realm of sustainable practices within the network provides a plethora of insights. The costs associated with these operations are considerable, standing at a staggering $435,341,145. Revenues garnered from recycled products offset a small portion of these costs, accounting for 3.92%. A deeper examination of the financial structure reveals that processing activities dominate expenditure, consuming a whopping 42.84%. This observation confirms the capital-intensive characteristics of the industry. However, the silver lining emerges in the form of revenue from recycling activities and sales of salvaged machinery. These earnings underscore the untapped potential within the ship-recycling industry, especially when viewed through the lens of a circular economy. For the industry to truly flourish and be profitable, a meticulous focus on cost optimization is crucial. This spans the gamut of operations from assembly to transportation. The roadmap for achieving this financial prudence lies in the assimilation of automation, embracing lean methodologies, investing in efficient tooling, dedicated training for the workforce, and the integration of state-of-the-art technology.

Through environmental assessment, we understand that CLSCN can help in the efficient recovery of materials and reduce negative environmental implications. The pie chart in Figure 41 shows the CO_2 emissions at various stages. A staggering 46.4% of the emissions come from metal processing due to energy-intensive smelting. Dismantling ships contributed 24.2% of the emissions, highlighting the energy demands of this phase. Recycling, typically seen as environmentally friendly, contributes to 15.1% of the emissions. The assembly and disposal stages contributed to 10.2% and 3.2%, respectively. The transportation of materials results in comparatively minimal emissions (1%). A sensitivity analysis, as illustrated in Figure 42, focuses on the costs. Among the parameters, the processing cost was the highest, with a 20% increase, leading to a total cost surge of 9.6%. Assembly and technological capital costs are also influential. The unpredictability of fuel and material prices leads to changes of 1.7% and 3.4%, respectively. Another sensitivity analysis, shown in Figure 43, provides insights into carbon emissions. In this case, metal processing remains significant. A 20% fluctuation in emissions influenced the network's emissions by 9.28%. The dismantling, recycling, assembling, transportation, and disposal processes have varying impacts.

Figure 45 provides a compelling visual representation of the circular economy model that serves as the foundation for this thesis' exploration of sustainable ship recycling. It exemplifies the groundbreaking CLSCN concept, which seeks to transform traditional shipbreaking practices into a regenerative and restorative process. The figure depicts the uninterrupted loop from shipbuilding to ship recycling, emphasizing the perpetual flow of materials through various stages, such as design, material recovery, and the resale of recovered components. This visual representation aligns with the thesis's central tenet that EoL ships represent not waste and environmental degradation, but rather the beginning of a new, value-added journey. It also reflects the thesis's findings that ship recycling can significantly reduce environmental risks, enhance economic value, and promote social welfare. Moreover, it echoes the call for policy reform and industry adaptation towards a sustainable model, underpinned by a rigorous environmental and economic assessment, as detailed in the study. This depiction of the circular hub, with its emphasis on innovation, zero-carbon emissions, and occupational health and safety, not only reflects the thesis's conclusion but also embodies its broader vision for an industry that balances economic viability with environmental stewardship.

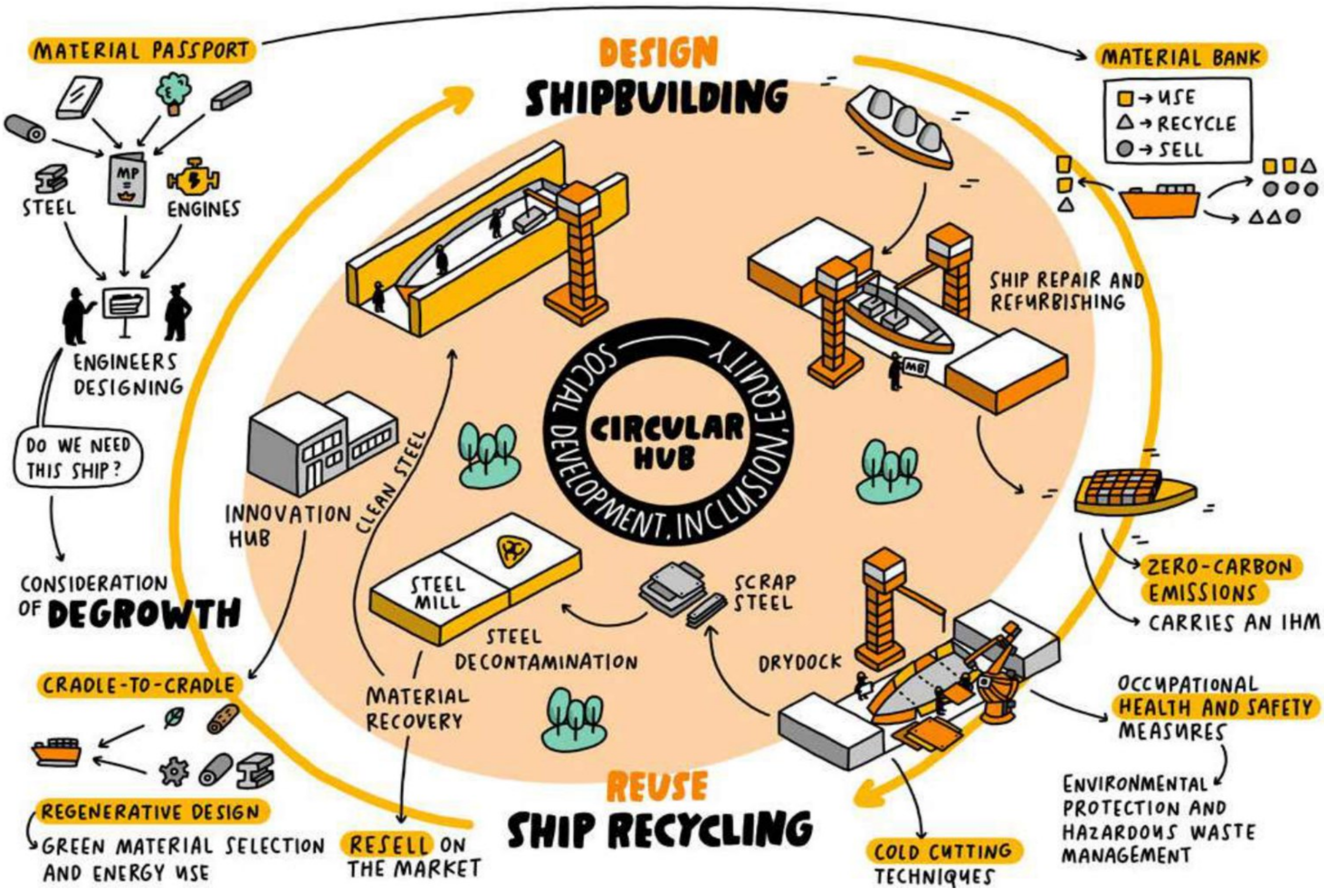


Figure 45. Anchoring Circular Innovation for Ship Recycling
Source: (Perivier et al., 2022)

5.2 Contribution to Knowledge

The ship recycling industry, traditionally marked by its resource-intensive and environmentally challenging processes, is undergoing a transformative shift towards sustainability and circularity. This thesis represents a significant contribution to this ongoing evolution, offering innovative insights and solutions that add substantial value to both the industry and broader knowledge base. The creation of a CLSCN for ship recycling, as proposed and analyzed in this research, has several key implications.

a) Sustainable Transformation: The proposed model has the power to instigate a paradigm shift within the ship recycling sector. By integrating circular economy principles, this study offers an industry roadmap for more sustainable practices. The adoption of such a model can substantially reduce waste, curb environmental pollution, and minimize the carbon footprint associated with ship recycling. This transition to sustainability aligns with global environmental objectives and elevates the industry's reputation as a steward of marine resources.
b) Economic Viability and Efficiency: The proposed network offers opportunities for cost reduction and improved operational efficiency within the ship-recycling industry. The economic viability of ship recycling operations can be strengthened by streamlining processes, optimizing transportation, and reducing waste. This study provides valuable insights into cost-effective strategies and network design, ultimately benefiting industry stakeholders.
c) Regulatory Compliance and Stakeholder Engagement: In era of increasing environmental regulations and stakeholder expectations, the closed-loop supply chain model can help the ship recycling industry meet compliance requirements and engage with stakeholders effectively. This research highlights the importance of aligning with regulatory standards and fostering positive relationships with environmental organizations, governmental bodies, and local communities surrounding recycling facilities.
d) Advancing Academic Knowledge: Beyond its industrial applications, this research contributes to the academic body of knowledge by expanding the understanding of closed-loop supply chain network design and optimization in the ship dismantling industry. As highlighted in the literature review chapter, few academic researchers have applied CE principles in this industry. It offers a practical case study based on estimated values rather than relying on real-world data.

5.3 Future Research

In this study, a comprehensive multi-objective optimization model was developed to minimize the cost and carbon emissions within a ship recycling network. The scope for future research in this domain is vast and has the potential to address various intricacies and uncertainties inherent in real-world applications. One avenue for future research is the incorporation of stochastic modeling to address uncertainties related to demand, supply, transportation times, and operational efficiencies, making the model more adaptable to real-world variations. This stochastic approach enhances the robustness of the model, allowing for more accurate and reliable decision making in the face of unpredictable factors. Furthermore, a more holistic environmental perspective can be incorporated by considering the environmental impacts beyond carbon emissions. By integrating factors such as water usage, waste generation, and other forms of pollution, the model can offer a more comprehensive assessment of sustainability, aligning more closely with the overarching environmental goals. Investigating the integration of renewable energy sources at different centers within the network is another potential research avenue. This exploration could lead to a decrease in reliance on non-renewable energy sources, thereby mitigating the environmental impact and aligning the model with green energy initiatives.

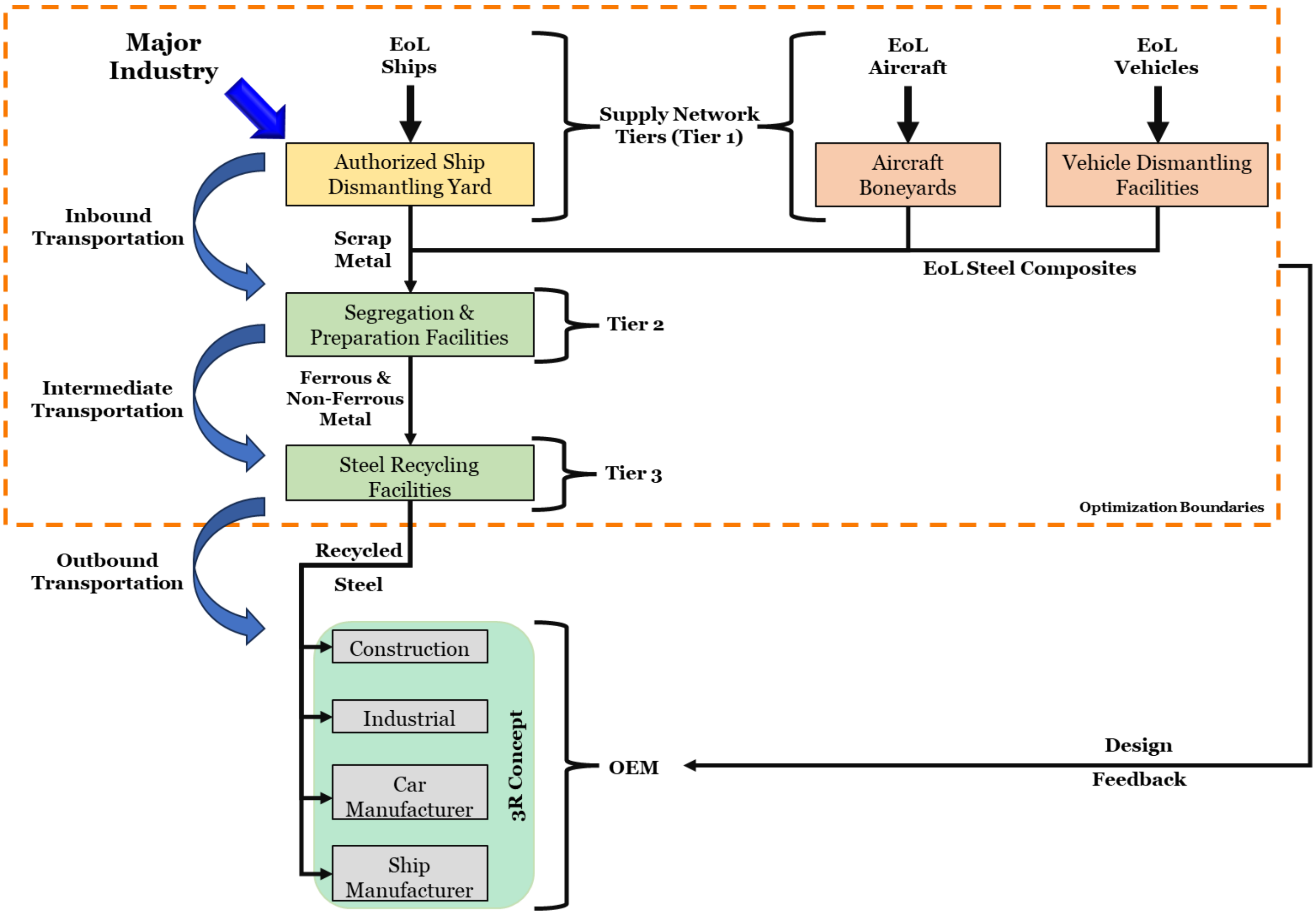


Figure 46. Macro Level Future Research

The model and solution approach employed in this study to devise an effective CLSCN can be extrapolated to other locations to assess the feasibility of remanufacturing EoL ships. This study focused on bulk carrier ships; however, another potential aspect could involve designing a multi-product approach. In the future, this study has the potential to expand to encompass additional sources and end-use sectors for recycled components. Figure 46 shows the proposed future research for the extended model (Macro Level), which can involve the integration of two similar industries: aircraft and vehicle dismantling. This expansion aims to amplify waste material volumes and includes similar industries, as there are many materials shared among the three major industries, thereby mitigating the tendency for centralized systems that entail extended transportation distances. This special extension will assess the scalability of the model by applying it to larger, more complex networks and analyzing the computational efficiency and solution quality.

Another extension to be considered is the scope of ship recycling will be broadened to encompass the entire shipbuilding process within the network (Figure 47). This comprehensive model will integrate the procurement of new parts and equipment essential for the construction of new vessels. It will also detail the delivery logistics of these newly built ships back to the ship owners, thereby creating a full-circle lifecycle for maritime vessels. This enhanced CLSCN aims to foster a seamless flow of materials and information, ensuring that the loop from the EoL bulk carriers ship to a remanufactured ship is closed efficiently, with sustainability and circular economy principles at its core.

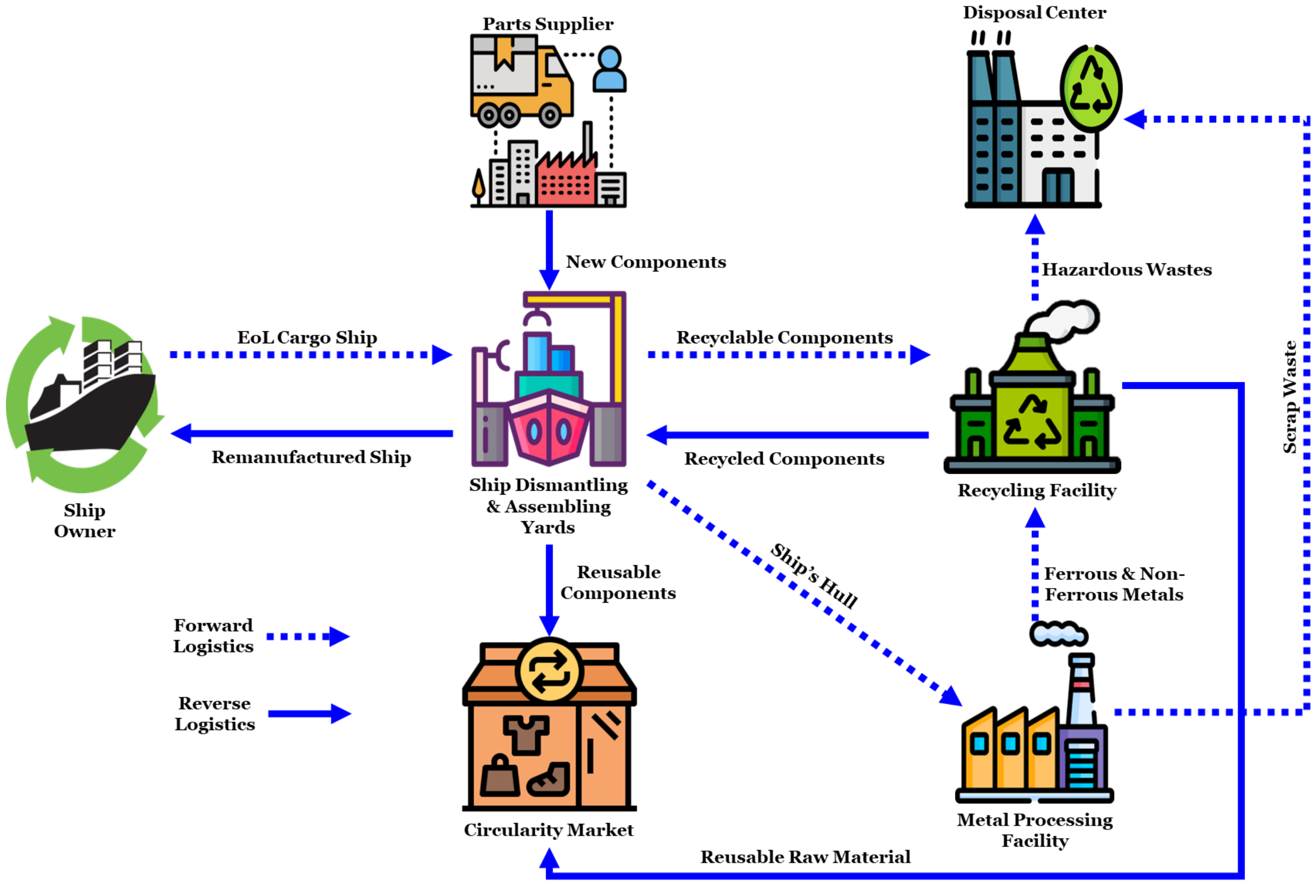


Figure 47. Future Extension for the CLSCN

This research illuminates a significant gap in the existing literature, where the predominant focus over the last two decades has been on analyzing the methods and risks associated with ship recycling. Notably, there is a conspicuous absence of studies exploring the integration of circular economy principles within this industry. By designing an optimized CLSCN and employing a MILP model for multi-objective optimization, this study pioneers bridging this gap. The insights gained from this study underscore the untapped potential of incorporating circular economy concepts, demonstrating tangible benefits in terms of cost reduction, energy efficiency, and reduced carbon emissions. The integration of economic and environmental objectives, as revealed by this study, paves the way for the development of more sustainable, efficient, and eco-friendly practices in the ship-recycling industry.

In summary, the creation of a closed-loop supply chain network for the ship recycling industry, as explored in this thesis, offers a multifaceted value proposition. It stands to revolutionize the industry's approach to sustainability, economics, technology, regulation, and academic inquiry, fostering a future in which ship recycling is not only economically viable but also a model of environmental stewardship and innovation. This master's thesis represents not just a culmination of academic endeavors, but also a roadmap toward a sustainable and responsible future for the ship recycling industry. By embracing the principles of a closed-loop supply chain, this study provides a compelling vision of an industry that thrives economically while preserving the environment and serving as a model of sustainability. The transformation of ship recycling, as envisaged in this thesis, is an imperative step toward shaping a more sustainable and responsible maritime industry that respects the seas it navigates and the resources it relies upon. This journey is not only a path forward for the ship recycling industry but also a symbol of hope for industries worldwide as they navigate the challenges of the twenty-first century and **sail towards sustainability**.

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APPENDIX 1: PYTHON CODE

```
# Install the required package
!pip install gurobipy
import numpy as np
import gurobipy as gp
from gurobipy import Model, GRB, quicksum

# Create the model
SCN = Model("CLSCN")

# ========== Indices and Sets ========== #
# Set N: Components (Recyclable, Reusable, Recycled, New)
N = ["n1", "n2", "n3", "n4", "n5", "n6", "n7", "n8"]
#n1= Plastic, n2= Glass, n3= Fluids, n4= Minerals, n5= Joinery, n6= Ferrous Metal, n7= Non-ferrous
Metal, n8= Machinery

# Set I: Locations of ship owner
I = ["i1", "i2", "i3"]

# Set K: Ships Dismantling Yards Locations
K = ["k1", "k2", "k3", "k4", "k5", "k6", "k7", "k8", "k9"]

# Set L: Metal Processing Facility
L = ["l1", "l2", "l3", "l4", "l5"]

# Set P: Disposal Centers
P = ["p1", "p2", "p3", "p4", "p5"]

# Set R: Recycling Facility
R = ["r1", "r2", "r3", "r4", "r5"]

# Set M: Circularity Markets
M = ["m1", "m2", "m3", "m4", "m5", "m6", "m7", "m8", "m9", "m10", "m11", "m12", "m13", "m14", "m15"]

# ========== Decision Variables ========== #
# Y_ik: Number of EoLS sent from location i of ship owner to SDY k
Y = {(i, k): SCN.addVar(vtype=GRB.CONTINUOUS, name=f"Y_{i}_{k}") for i in I for k in K}

# B_kl: Amount of bulk materials sent from SDY k to metal processing facility l
B = {(k, l): SCN.addVar(vtype=GRB.CONTINUOUS, name=f"B_{k}_{l}") for k in K for l in L}

# S_nkm: Number of subcomponent/material n of EoLS sold by SDY k to Circularity market m
S_dict = {(n, k, m): SCN.addVar(vtype=GRB.CONTINUOUS, name=f"S_{n}_{k}_{m}") for n in N for k in K
for m in M}

# A_nkr: Amount of subcomponent/material n of EoLS sent from SDY k to recycling facility r
A = {(n, k, r): SCN.addVar(vtype=GRB.CONTINUOUS, name=f"A_{n}_{k}_{r}") for n in N for k in K for r
in R}

# G_nlr: Amount of bulk materials sent from metal processing facility l to recycling facility r
G = {(n, l, r): SCN.addVar(vtype=GRB.CONTINUOUS, name=f"G_{n}_{l}_{r}") for n in N for l in L for r
in R}
```

```
# Distance between SDY k and metal processing facility l
D_kl = {
    'k1': {'l1': 223, 'l2': 553, 'l3': 713, 'l4': 416, 'l5': 864},
    'k2': {'l1': 286, 'l2': 378, 'l3': 674, 'l4': 577, 'l5': 783},
    'k3': {'l1': 448, 'l2': 138, 'l3': 342, 'l4': 496, 'l5': 651},
    'k4': {'l1': 486, 'l2': 152, 'l3': 275, 'l4': 441, 'l5': 548},
    'k5': {'l1': 578, 'l2': 225, 'l3': 275, 'l4': 338, 'l5': 518},
    'k6': {'l1': 612, 'l2': 312, 'l3': 246, 'l4': 283, 'l5': 493},
    'k7': {'l1': 886, 'l2': 462, 'l3': 316, 'l4': 89, 'l5': 146},
    'k8': {'l1': 924, 'l2': 572, 'l3': 394, 'l4': 137, 'l5': 97},
    'k9': {'l1': 980, 'l2': 671, 'l3': 571, 'l4': 267, 'l5': 132}
}

# Distance between SDY k and recycling facility r
D_kr = {
    'k1': {'r1': 133, 'r2': 573, 'r3': 513, 'r4': 616, 'r5': 884},
    'k2': {'r1': 73, 'r2': 368, 'r3': 474, 'r4': 567, 'r5': 793},
    'k3': {'r1': 438, 'r2': 156, 'r3': 142, 'r4': 486, 'r5': 671},
    'k4': {'r1': 476, 'r2': 92, 'r3': 121, 'r4': 431, 'r5': 538},
    'k5': {'r1': 588, 'r2': 115, 'r3': 225, 'r4': 358, 'r5': 528},
    'k6': {'r1': 622, 'r2': 142, 'r3': 266, 'r4': 383, 'r5': 483},
    'k7': {'r1': 886, 'r2': 452, 'r3': 312, 'r4': 189, 'r5': 126},
    'k8': {'r1': 934, 'r2': 566, 'r3': 376, 'r4': 231, 'r5': 97},
    'k9': {'r1': 990, 'r2': 689, 'r3': 581, 'r4': 277, 'r5': 79},
}

# Distance between metal processing facility l and recycling facility r
D_lr = {
    'l1': {'r1': 118, 'r2': 388, 'r3': 435, 'r4': 477, 'r5': 580},
    'l2': {'r1': 237, 'r2': 115, 'r3': 107, 'r4': 159, 'r5': 231},
    'l3': {'r1': 448, 'r2': 78, 'r3': 105, 'r4': 145, 'r5': 185},
    'l4': {'r1': 559, 'r2': 151, 'r3': 96, 'r4': 112, 'r5': 128},
    'l5': {'r1': 782, 'r2': 332, 'r3': 288, 'r4': 252, 'r5': 105},
}

# Distance between metal processing facility l and disposal center p
D_lp = {
    'l1': {'p1': 115, 'p2': 501, 'p3': 672, 'p4': 623, 'p5': 769},
    'l2': {'p1': 387, 'p2': 139, 'p3': 630, 'p4': 189, 'p5': 492},
    'l3': {'p1': 407, 'p2': 118, 'p3': 553, 'p4': 148, 'p5': 349},
    'l4': {'p1': 444, 'p2': 127, 'p3': 313, 'p4': 114, 'p5': 328},
    'l5': {'p1': 486, 'p2': 222, 'p3': 479, 'p4': 98, 'p5': 134},
}

# Distance between recycling facility r and disposal center p
D_rp = {
    'r1': {'p1': 112, 'p2': 451, 'p3': 358, 'p4': 571, 'p5': 655},
    'r2': {'p1': 356, 'p2': 129, 'p3': 186, 'p4': 216, 'p5': 369},
    'r3': {'p1': 406, 'p2': 152, 'p3': 104, 'p4': 154, 'p5': 283},
    'r4': {'p1': 563, 'p2': 166, 'p3': 157, 'p4': 87, 'p5': 156},
    'r5': {'p1': 797, 'p2': 371, 'p3': 368, 'p4': 114, 'p5': 95}
}
```

```
# Distance between SDY k and circularity market m
D_km = {
    'k1': {'m1': 72, 'm2': 106, 'm3': 128, 'm4': 144, 'm5': 89, 'm6': 191, 'm7': 281, 'm8': 295,
'm9': 310, 'm10': 322, 'm11': 345, 'm12': 361, 'm13': 392, 'm14': 423, 'm15': 488},
    'k2': {'m1': 105, 'm2': 125, 'm3': 185, 'm4': 124, 'm5': 73, 'm6': 115, 'm7': 189, 'm8': 203,
'm9': 224, 'm10': 265, 'm11': 278, 'm12': 288, 'm13': 301, 'm14': 329, 'm15': 365},
    'k3': {'m1': 188, 'm2': 194, 'm3': 225, 'm4': 230, 'm5': 159, 'm6': 84, 'm7': 142, 'm8': 168,
'm9': 182, 'm10': 201, 'm11': 216, 'm12': 232, 'm13': 251, 'm14': 264, 'm15': 321},
    'k4': {'m1': 245, 'm2': 269, 'm3': 315, 'm4': 285, 'm5': 267, 'm6': 234, 'm7': 104, 'm8': 88,
'm9': 96, 'm10': 113, 'm11': 142, 'm12': 182, 'm13': 230, 'm14': 251, 'm15': 288},
    'k5': {'m1': 322, 'm2': 348, 'm3': 389, 'm4': 325, 'm5': 311, 'm6': 219, 'm7': 118, 'm8': 78,
'm9': 79, 'm10': 132, 'm11': 172, 'm12': 186, 'm13': 244, 'm14': 267, 'm15': 318},
    'k6': {'m1': 351, 'm2': 378, 'm3': 466, 'm4': 447, 'm5': 427, 'm6': 247, 'm7': 126, 'm8': 113,
'm9': 97, 'm10': 141, 'm11': 192, 'm12': 207, 'm13': 272, 'm14': 293, 'm15': 340},
    'k7': {'m1': 603, 'm2': 638, 'm3': 664, 'm4': 582, 'm5': 563, 'm6': 310, 'm7': 152, 'm8': 163,
'm9': 144, 'm10': 126, 'm11': 76, 'm12': 66, 'm13': 117, 'm14': 102, 'm15': 178},
    'k8': {'m1': 636, 'm2': 647, 'm3': 668, 'm4': 622, 'm5': 608, 'm6': 579, 'm7': 313, 'm8': 334,
'm9': 317, 'm10': 234, 'm11': 178, 'm12': 87, 'm13': 111, 'm14': 93, 'm15': 150},
    'k9': {'m1': 680, 'm2': 716, 'm3': 745, 'm4': 685, 'm5': 661, 'm6': 585, 'm7': 411, 'm8': 447,
'm9': 413, 'm10': 277, 'm11': 196, 'm12': 130, 'm13': 105, 'm14': 68, 'm15': 118},
}

# Distance between recycling facility r and circularity market m
D_rm = {
    "r1": {"m1": 125, "m2": 179, "m3": 211, "m4": 117, "m5": 47, "m6": 176, "m7": 246, "m8": 264,
"m9": 280, "m10": 299, "m11": 311, "m12": 334, "m13": 376, "m14": 410, "m15": 560},
    "r2": {"m1": 499, "m2": 518, "m3": 547, "m4": 568, "m5": 509, "m6": 280, "m7": 113, "m8": 78,
"m9": 103, "m10": 145, "m11": 166, "m12": 188, "m13": 259, "m14": 281, "m15": 388},
    "r3": {"m1": 572, "m2": 597, "m3": 616, "m4": 465, "m5": 441, "m6": 321, "m7": 57, "m8": 133,
"m9": 145, "m10": 142, "m11": 155, "m12": 188, "m13": 229, "m14": 272, "m15": 344},
    "r4": {"m1": 594, "m2": 622, "m3": 653, "m4": 627, "m5": 615, "m6": 343, "m7": 124, "m8": 156,
"m9": 125, "m10": 142, "m11": 111, "m12": 163, "m13": 181, "m14": 209, "m15": 328},
    "r5": {"m1": 681, "m2": 638, "m3": 641, "m4": 633, "m5": 611, "m6": 562, "m7": 489, "m8": 518,
"m9": 465, "m10": 448, "m11": 381, "m12": 204, "m13": 70, "m14": 95, "m15": 119},
}

# Cost Parameters (in $)
# Opening cost of metal processing facility l
F_l =  {'l1': 1.5e6, 'l2': 1.5e6, 'l3': 1.5e6, 'l4': 1.5e6, 'l5': 1.5e6}

# Opening cost of SDY k
F_k =  {'k1': 3e7, 'k2': 3e7, 'k3': 3e7, 'k4': 3e7, 'k5': 3e7, 'k6': 3e7, 'k7': 3e7, 'k8': 3e7,
'k9': 3e7}

# Collection cost of EoLS in SDY k (in $/ton)
CC_k = {'k1': 500, 'k2': 500, 'k3': 500, 'k4': 500, 'k5': 500, 'k6': 500, 'k7': 500, 'k8': 500,
'k9': 500}

# Dismantling cost of EoLS in SDY k (in $/ton)
DC_k = {'k1': 700, 'k2': 700, 'k3': 700, 'k4': 700, 'k5': 700, 'k6': 700, 'k7': 700, 'k8': 700,
'k9': 700}

# Processing cost in metal processing facility l (in $/ton)
SC_k = {'k1': 800, 'k2': 800, 'k3': 800, 'k4': 800, 'k5': 800, 'k6': 800, 'k7': 800, 'k8': 800,
'k9': 800}
```

```
# Disposal cost at the disposal center p (in $/ton)
LC_p = {'p1': 150, 'p2': 150, 'p3': 150, 'p4': 150, 'p5': 150}

# Recycling cost at the recycling facility r (in $/ton)
RC_r = {'r1': 200, 'r2': 200, 'r3': 200, 'r4': 200, 'r5': 200}

# Average transportation cost of components/materials within the network (in $/ton/km)
t = 3
# Price Parameters (in $/ton)

# Unit price of component/material n sent from SDY k to the second-hand product markets m
UP_nkm = {'n1': 300, 'n2': 350, 'n3': 200, 'n4': 250, 'n5': 250, 'n8': 850}

# Unit price of component/material n sent from recycling facility r to the second-hand product
markets m
UP_nkm = {'n1': 250, 'n2': 350, 'n3': 450, 'n4': 350, 'n5': 250, 'n6': 550, 'n7': 650}

# Purchasing price of component/material n sent from supplier s to SDY k
PP_nsk_dict = {}
for n in N:
    PP_nsk_dict[n] = {}
    for s in S:
        PP_nsk_dict[n][s] = {}
        for k in K:
            PP_nsk_dict[n][s][k] = 100

# Emissions Parameters (in kgCO2 and kgCO2/(km*ton))

# Maximum allowable total CO2 emissions
CE_max = 10000

# CO2 emissions per km per ton during transportation
CE_trans = 0.06

# CO2 emissions that produced from component/material n at SDY k (in kgCO2/ton)
CE_nk = {
     "n1": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},
     "n2": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},
     "n3": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},
     "n4": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},
     "n5": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},
     "n6": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},
     "n7": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},
     "n8": {"k1": 100, "k2": 100, "k3": 100, "k4": 100, "k5": 100, "k6": 100, "k7": 100, "k8": 100,
"k9": 100},

}
```

```python
# CO2 emissions that produced from component/material n at recycling facility r (in kgCO2/ton)
CE_nr = {
     "n1": {"r1": 150, "r2": 150, "r3": 150, "r4": 150, "r5": 150},
     "n2": {"r1": 150, "r2": 150, "r3": 150, "r4": 150, "r5": 150},
     "n3": {"r1": 150, "r2": 150, "r3": 150, "r4": 150, "r5": 150},
     "n4": {"r1": 150, "r2": 150, "r3": 150, "r4": 150, "r5": 150},
     "n5": {"r1": 150, "r2": 150, "r3": 150, "r4": 150, "r5": 150},
     "n6": {"r1": 150, "r2": 150, "r3": 150, "r4": 150, "r5": 150},
     "n7": {"r1": 150, "r2": 150, "r3": 150, "r4": 150, "r5": 150},
}

# CO2 emissions that produced from component/material n at disposal center p (in kgCO2/ton)
CE_np ={
     "n1": {"p1": 80, "p2": 80, "p3": 80, "p4": 80, "p5": 80},
     "n2": {"p1": 80, "p2": 80, "p3": 80, "p4": 80, "p5": 80},
     "n3": {"p1": 80, "p2": 80, "p3": 80, "p4": 80, "p5": 80},
     "n4": {"p1": 80, "p2": 80, "p3": 80, "p4": 80, "p5": 80},
     "n5": {"p1": 80, "p2": 80, "p3": 80, "p4": 80, "p5": 80},
     "n6": {"p1": 80, "p2": 80, "p3": 80, "p4": 80, "p5": 80},
     "n7": {"p1": 80, "p2": 80, "p3": 80, "p4": 80, "p5": 80},

}

# CO2 emissions that produced from component/material n at metal processing facility l (in
kgCO2/ton)
CE_nl = {
     "n6": {"l1": 1000, "l2": 1000, "l3": 1000, "l4": 1000, "l5": 1000},
     "n7": {"l1": 1000, "l2": 1000, "l3": 1000, "l4": 1000, "l5": 1000},
}

# Ratio Parameters (Unitless)
alpha = {
    1: 0.9, # Ratio of hull weight to whole EoLS weight (0 ≤ α_1  ≤1)
    2: 0.75,# Ratio of weight of reusable subcomponents/materials to whole EoLS weight (0 ≤ α_2  ≤1)
    3: 0.25,# Ratio of weight of non-reusable subcomponents/materials to whole EoLS weight(α_2+
α_3=1)
    4: 0.3, # Ratio of weight of SW within the hull (0 ≤ α_4  ≤1)
    5: 0.9, # Ratio of recyclable materials within the hull (0 ≤ α_5  ≤1)
    6: 0.1, # Ratio of disposed materials within the recycled material (0 ≤ α_6  ≤1)
}

# Ratio of the weight of component/material n to whole EoLS weight
rat_n = {'n1': 0.012, 'n2': 0.01, 'n3': 0.01, 'n4': 0.025, 'n5': 0.013, 'n6': 0.01, 'n7': 0.85,
'n8': 0.07}

# ========== Constraints ========== #

# Flow Constraints

# Constraint (9)
for k in K:
    SCN.addConstr(sum(B[k, l] for l in L) == alpha[1] * sum(Y[i, k] for i in I))
```

```
# Constraint (10)
for k in K:
    for s in S:
 SCN.addConstr(sum(C[n, s, k] for n in ["n8"]) == alpha[7] * rat_n[n] *  sum(Y[i, k] for i in I))

# Constraint (11)
for k in K:
    for s in S:
        SCN.addConstr(sum(S_dict[n, k, m] for n in ["n8"] for m in M) == alpha[2] * rat_n[n] *
sum(Y[i, k] for i in I))

# Constraint (12)
for k in K:
    for m in M:
 SCN.addConstr(sum(S_dict[n, k, m] for n in ["n8"]) == sum(C[n, s, k] for s in S for n in ["n8"]))

# Constraint (13)
for k in K:
    for n in N[:5]: # Only consider the first 5 elements of N
        SCN.addConstr(sum(A[n, k, r] for r in R) == alpha[3] * rat_n[n] * sum(Y[i, k] for i in I))

# Constraint (14)
for l in L:
    for n in N ["n3", "n4", "n5"]:
        SCN.addConstr(sum(E[l, p] for p in P) == alpha[4] * rat_n[n] * sum(B[k, l] for k in K))

# Constraint (15)
for l in L:
    for n in N["n6", "n7"]:
        SCN.addConstr(sum(G[n, l, r] for r in R) == alpha[5] * rat_n[n] * sum(B[k, l] for k in K))

# Constraint (16)
for r in R:
    for n in ["n1", "n2", "n3", "n4", "n5"]:
        SCN.addConstr(sum(F[n, r, p] for p in P) == alpha[6] * sum(A[n, k, r] for k in K))

# Constraint (17)
for r in R:
    for n in ["n6", "n7"]:
        SCN.addConstr(sum(F[n, r, p] for p in P) == alpha[6] * sum(G[n, l, r] for l in L))

# Constraint (18)
for r in R:
    for n in ["n1", "n2", "n3", "n4", "n5"]:
        SCN.addConstr(sum(FM[n, r, m] for m in M) == (1 - alpha[6]) * sum(A[n, k, r] for k in K))


# Constraint (19)
for r in R:
    for n in ["n6", "n7"]:
        SCN.addConstr(sum(FM[n, r, m] for m in M) == (1 - alpha[6]) * sum(G[n, l, r] for l in L))

# Constraint (20)
for r in R:
    for n in ["n1", "n2", "n3", "n4", "n5"]:
        SCN.addConstr(sum(R_dec[n, r, k] for k in K) == alpha[8] * sum(A[n, k, r] for k in K))
```

```
# Constraint (21)
for r in R:
    for n in ["n6", "n7"]:
        SCN.addConstr(sum(R_dec[n, r, k] for k in K) == alpha[8] * sum(G[n, l, r] for l in L))

# Capacity Constraints

# Constraint (22)
for k in K:
    SCN.addConstr(sum(Y[i, k] for i in I) <= CAP_k[k] * e_k[k])

# Constraint (23)
for l in L:
    SCN.addConstr(sum(B[k, l] for k in K) <= CAP_l[l] * e_l[l])

# Constraint (24)
for r in R:
    for n in ["n1", "n2", "n3", "n4", "n5", "n6", "n7"]:
        SCN.addConstr(sum(A[n, k, r] for k in K) + sum(G[n, l, r] for l in L) <= CAP_nr[n][r])

# Constraint (24)
for p in P:
    SCN.addConstr(sum(E[l, p] for l in L) + sum(F[n, r, p] for n in N for r in R) <= CAP_p[p])

# Non-negativity constraints - Constraint (25)
for i in I:
    for k in K:
        SCN.addConstr(Y[i, k] >= 0)
        SCN.addConstr(W[k, i] >= 0)
    for n in N:
        for r in R:
            SCN.addConstr(A[n, k, r] >= 0)
        for l in L:
            SCN.addConstr(B[k, l] >= 0)

for n in N:
    for m in M:
        for k in K:
            SCN.addConstr(S_dict[n, k, m] >= 0)

for n in N:
    for r in R:
        for l in L:
            SCN.addConstr(G[n, l, r] >= 0)
        for p in P:
            SCN.addConstr(F[n, r, p] >= 0)
        for m in M:
            SCN.addConstr(FM[n, r, m] >= 0)
        for k in K:
            SCN.addConstr(R_dec[n, r, k] >= 0)
for l in L:
    for p in P:
        SCN.addConstr(E[l, p] >= 0)
```

```
for s in S:
    for n in N:
        for k in K:
            SCN.addConstr(C[n, s, k] >= 0)

# Binary constraints - Constraint (26)
for k in K:
    SCN.addConstr(e_k[k] >= 0)
    SCN.addConstr(e_k[k] <= 1)

for l in L:
    SCN.addConstr(e_l[l] >= 0)
    SCN.addConstr(e_l[l] <= 1)

# Emissions Constraints
# Constraint (27)
for n in N:
    emissions1 = (
        sum(D_sk[s][k] * C[n, s, k] * CE_trans for s in S for k in K) +
        sum(D_kl[k][l] * B[k, l]         * CE_trans for k in K for l in L) +
        sum(D_rk[r][k] * R_dec[n, r, k]  * CE_trans for r in R for k in K) +
        sum(D_kr[k][r] * A[n, k, r]      * CE_trans for k in K for r in R) +
        sum(D_lr[l][r] * G[n, l, r]      * CE_trans for l in L for r in R) +
        sum(D_lp[l][p] * E[l, p]         * CE_trans for l in L for p in P) +
        sum(D_rp[r][p] * F[n, r, p]      * CE_trans for r in R for p in P) +
        sum(D_km[k][m] * S_dict[n, k, m] * CE_trans for k in K for m in M) +
        sum(D_rm[r][m] * FM[n, r, m]     * CE_trans for r in R for m in M)
    )
    SCN.addConstr(emissions1 <= CE_max)
# Constraint (28)
for n in N:
    emissions2 = (
        sum(Y[i, k] * CE_nk[n][k] for i in I for k in K) +
        sum(C[n, s, k] * CE_nk[n][k] for s in S for k in K if n in ['n8']) +
        sum(R_dec[n, r, k] * CE_nk[n][k] for r in R for k in K if n in
['n1','n2','n3','n4','n5','n6','n7']) +
        sum(A[n, k, r] * CE_nr[n][r] for k in K for r in R if n in ['n1','n2','n3','n4','n5']) +
        sum(G[n, l, r] * CE_nr[n][r] for l in L for r in R if n in ['n6', 'n7']) +
        sum(F[n, r, p] * CE_np[n][p] for r in R for p in P if n in ['n1','n2','n3','n4','n5','n6',
'n7']) +
        sum(B[k, l] * CE_nl[n][l] for k in K for l in L if n in ['n6', 'n7'])
    )
    SCN.addConstr(emissions2 <= CE_max)
# ========== OBJECTIVE FUNCTIONS ========== #

# Objective function: min Z= TCE + TC
TCE = (
      quicksum(D_sk[s][k] * C[n, s, k] * CE_trans for n in ['n8'] for s in S for k in K)
    + quicksum(D_kl[k][l] * B[k, l] * CE_trans for k in K for l in L)
    + quicksum(D_rk[r][k] * R_dec[n, r, k] * CE_trans for n in ['n1','n2','n3','n4','n5','n6','n7']
for r in R for k in K)
    + quicksum(D_kr[k][r] * A[n, k, r] * CE_trans for n in ['n1','n2','n3','n4','n5'] for k in K for
r in R)
    + quicksum(D_lr[l][r] * G[n, l, r] * CE_trans for n in ['n6', 'n7'] for l in L for r in R)
    + quicksum(D_rp[r][p] * F[n, r, p] * CE_trans for n in ['n1','n2','n3','n4','n5','n6', 'n7']for
r in R for p in P)
```

```
    + quicksum(D_lp[l][p] * E[l, p] * CE_trans for l in L for p in P)
    + quicksum(D_rm[r][m] * FM[n, r, m] * CE_trans for n in ['n1','n2','n3','n4','n5','n6', 'n7']for
r in R for m in M)
    + quicksum(D_km[k][m] * S_dict[n, k, m] * CE_trans for n in ['n8'] for k in K for m in M)
    + quicksum(Y[i, k] * CE_nk[n][k] for n in N for i in I for k in K)
    + quicksum(W[k, i] * CE_nk[n][k] for n in N for i in I for k in K)
    + quicksum(C[n, s, k] * CE_nk[n][k] for n in ['n8'] for s in S for k in K)
    + quicksum(R_dec[n, r, k] * CE_nk[n][k] for n in ['n1','n2','n3','n4','n5','n6','n7'] for r in R
for k in K)
    + quicksum(A[n, k, r] * CE_nr[n][r] for n in ['n1','n2','n3','n4','n5'] for k in K for r in R)
    + quicksum(G[n, l, r] * CE_nr[n][r] for n in ['n6', 'n7'] for l in L for r in R)
    + quicksum(F[n, r, p] * CE_np[n][p] for n in ['n1','n2','n3','n4','n5','n6', 'n7'] for r in R
for p in P)
    + quicksum(B[k, l] * CE_nl[n][l] for n in ['n6', 'n7'] for k in K for l in L)
)
TC = (
      quicksum(F_l[l] * e_l[l] for l in L)
    + quicksum(F_k[k] * e_k[k] for k in K)
    + quicksum(Y[i, k] * CC_k[k] for i in I for k in K)
    + quicksum(A[n, k, r] * D_kr[k][r] * t for n in N for k in K for r in R)
    + quicksum(B[k, l] * D_kl[k] [l] * t for k in K for l in L)
    + quicksum(G[n, l, r] * D_lr[l][r] * t for n in N for l in L for r in R)
    + quicksum(F[n, r, p] * D_rp[r][p] * t for n in N for r in R for p in P)
    + quicksum(E[l, p] * D_lp[l][p] * t for l in L for p in P)
    + quicksum(FM[n, r, m] * D_rm[r][m] * t for n in N for r in R for m in M)
    + quicksum(R_dec[n, r, k] * D_rk[r][k] * t for n in N for r in R for k in K)
    + quicksum(C[n, s, k] * D_sk[s][k] * t for n in N for s in S for k in K)
    + quicksum(Y[i, k] * DC_k[k] for i in I for k in K)
    + quicksum(B[k, l] * SC_k[k] for k in K for l in L)
    + quicksum(A[n, k, r] * RC_r[r] for n in N for k in K for r in R)
    + quicksum(G[n, l, r] * RC_r[r] for n in N for l in L for r in R)
    + quicksum(W[k, i] * AC_k[k] for k in K for i in I)
    + quicksum(E[l, p] * LC_p[p] for l in L for p in P)
    + quicksum(F[n, r, p] * LC_p[p] for n in N for r in R for p in P)
    + quicksum(C[n, s, k] * PP_nsk_dict[n][s][k] for n in N for s in S for k in K)
    - quicksum(S_dict[n, k, m] * UP_nkm_dict[n][k][m] for n in N for k in K for m in M)
    - quicksum(FM[n, r, m] * UP_nrm_dict[n][r][m] for n in N for r in R for m in M)
      )
SCN.setObjective(TCE + TC, GRB.MINIMIZE)
# ========== Solution & Output ========== #
# Solve
SCN.optimize()

#Print Model Status:
print("Model Status:", SCN.status)

if SCN.status == GRB.Status.INFEASIBLE:
    print("The model cannot be solved because it is infeasible.")

#Print Objective Value:
print('The model is feasible with an objective value of:', SCN.objVal)

#Print Variable Values:
for v in SCN.getVars():
    print(f"{v.varName} = {v.x}")
```

```
# ========== Performing IIS ========== #

# Optionally, consider performing IIS to identify the conflicting constraints
# Compute the Irreducible Infeasible Subsystem
#    SCN.computeIIS()

# Write the IIS to a file
#    SCN.write("model.ilp")

# Print out the constraints that are part of the IIS directly:
#    for c in SCN.getConstrs():
#       if c.IISConstr:
#            print('%s' % c.constrName)
#else:
#    print('Model status is:', SCN.status)
# ========== Parameters Tunning ========== #

# Start parameter tuning
# By default, the tuning tool will test a wide range of parameter settings.
# You can also specify specific parameters to tune by providing them in the call.

#SCN.tune()

# If the tuning process found better parameters, apply them to the model.
#if SCN.tuneResultCount > 0:
    # Load the best set of parameters into the model
#    SCN.getTuneResult(0)
    # Write tuned parameters to a file (optional, but can be helpful for future reference)
#    SCN.write("tuned.prm")

# ========== Printing Out Parameters & Constraints ========== #

# You can print other parameters in a similar manner to inspect their values
#print("D_sk:", D_sk)

#Print Constraints: If there are any issues with the constraints, you can print them out to verify
their correctness
#for c in SCN.getConstrs():
#    print(c.ConstrName, c.Pi)

# ========== Model Log ========== #

#Model Log: To see the progress of the solver, you can set the verbosity level of the solver:
#SCN.Params.OutputFlag = 1  # 1 for verbose, 0 to mute

# ========== Model Suggestions ========== #

#Data Input: Use pandas or Excel for data input, especially if you're dealing with large data. This
would make it more readable and manageable.

#Sensitivity Analysis: This allows you to see how changes in certain parameters (e.g.,
transportation costs, emissions limits, etc.) can affect your objective function and decisions.

#Visualization: Once you've obtained the results, consider visualizing the supply chain network
using libraries like network and matplotlib.
```