

Advancing Safer and More Efficient South Asian Ship Recycling Facilities

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Abstract

Ship recycling yards play an integral role in the economy and in managing environmental hazards by facilitating the entire ship recycling process. Ship owners from all over the world sell End of Life (EOL) ships to the yard owners. The majority of these ships are sent to the yards in South Asian recycling countries, as these yards offer better prices for the ships. It is the substantially low wages of the workers which mainly enable the yard owners to bid a better price in the yard market, not the efficiency of the yards. Moreover, worker safety is often compromised due to the owners' reluctance to implement safety measures and their dependence on outdated recycling methods. If the overall efficiency of the recycling process is improved, the efficiency of the entire yard will increase, and workers will have a better working environment. With this goal, the current study investigates the structural and safety issues of the ship recycling industry. It introduces a new method named "Combination Concept" by integrating two methods – Early Vessel Separation (EVS) and Stage-Wise Dismantling System (SWS). This study also proposes a new layout which divides the entire yard area into two segments for better workflow and efficiency. The FlexSim simulation validates the efficiency and material handling capabilities of this layout. This study also developed a cutting sequence designed explicitly for double-hull tanker ships. This advised sequence ensures the safety of the workers and improves scrap value. Based on the investigation, this study successfully provided a set of recommendations for safer and more sustainable ship recycling, aligning with relevant regulations. The effectiveness of these recommendations will heavily depend on coordination between the government and yard owners, implementation, adequate training and the existence of modern infrastructure.

Keywords

Ship Recycling, Worker Safety, Environmental Hazards, FlexSim, Cutting Sequence

1. Introduction

Ship recycling refers to the process of breaking EOL (End of Life) ships to recycle and reuse them for various purposes. Generally, ships have an operational lifespan of 25 to 30 years. After this long service period, maintaining the ship becomes economically impractical, as the ship is no longer remains capable of providing sufficient returns. Moreover, due to inefficient machinery and the accumulation of toxic materials, the ship becomes more hazardous. After the end of a ship's service in the maritime industry, it starts a new phase in the ship recycling sector. Nearly 98% of a ship's weight can be reused in this process, only the remaining 2% needs to be disposed [1]. This number reflects the high efficiency of this process. The majority of the raw materials needed in the steel and other local industries are supplied by the ship recycling industry. As a result, reduced CO₂ is released into the environment. Thus, the process plays an essential role in conserving the source and minimising environmental pollution.

Additionally, the ship recycling industry makes a significant contribution to the economies of several developing nations, including Bangladesh, India, Pakistan, Turkey, and China. These countries have central shipbreaking yards that provide employment to thousands of people and support local industries.

However, despite these advantages, the industry faces several challenges. With economic development, environmental and social issues have become increasingly significant, especially after the migration of shipbreaking activities to South Asian nations [2]. Southeast Asia recycles a significantly higher number of ships than other parts of the world, generating substantial profits. At the same time, it also faces additional challenges related to worker safety, environmental hazards, and operational inefficiencies. These issues need to be addressed to develop safer and more efficient ship recycling practices that adhere to global sustainability and labour standards.

1.1. Background of the Ship Recycling Industry

Historically, ship recycling was limited in developed nations, such as the United States and Europe, during the 1960s. However, the industry shifted to South Asian countries over time, primarily due to these regions' lower wages and minimal safety regulations. This relocation enabled greater profit generation. The industry has become a leading economic contributor in the economies of countries like Bangladesh, India, and Pakistan. Ship recycling is a significant source of revenue and employment in these countries. **Figure 1** illustrates the primary countries involved in ship recycling in recent years. It is evident from the figure that Southeast

Asia dominated more than two-thirds of the total market share in 2013. In India, Alang Ship Breaking Yard alone generates an annual turnover of USD 521 million [3]. In spite of offering substantial economic benefits, it also poses severe risks to workers' safety and the environment. The conditions under which ships are recycled in Alang and other locations are hazardous.

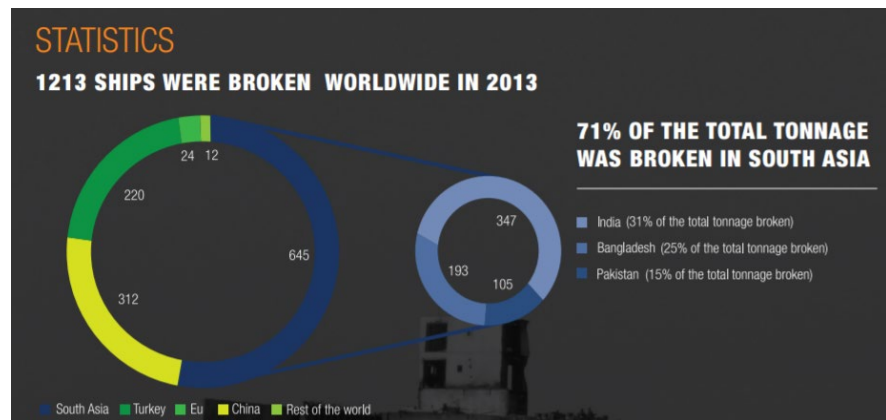


Figure 1. Statistics of the leading ship recycling countries [4].

Over the years, the environmental impact has become a much greater concern. Almost every component of a ship is reused during the recycling process. Some of them are recycled and reused, while the rest are resold on the market. Despite its advantages, the industry faces criticism due to poor working conditions, worker safety, and environmental degradation. **Table 1** [5] provides an overview of the statistical data related to ship recycling activities in Alang.

Table 1. Alang ship recycling statistics [5].

Performance Indicator	Frequency	Quantity	Unit
Tonnage Received	Annual	2.8 million	LDT
Ship Received	Annual	300	Ships
Average Ship Size Received	Annual	9300	LDT
Direct Employment	Constant	30,000	Persons
Re-rollable Steel Output	Annual	2 million	Tonnes
Steel Plate/Strips Loaded	Daily	6500	Tonnes
Truck Shipments of Flat Steel	Daily	430	Trucks
Industry Turnover	Annual	521 million	USD
Government Tax Revenue	Annual	83 million	USD
Gujarat Maritime Board/(GMB) Revenue	Annual	17 million	USD
Waste (Hazardous & Non-Hazardous)	Annual	5800	Tonnes
Accidental Deaths	Annual	19	Persons

1.2. Conventions and Regulations

The shift of the ship recycling industry to underdeveloped countries has raised

numerous concerns regarding worker safety and environmental impact. These concerns are legit, as workers in these industries are often exposed to hazardous materials such as asbestos and PCBs. Moreover, they often work without adequate personal protective equipment (PPE). As a result, fatalities have become a typical incident in these yards.

The Basel Convention (1992) was the first international legal instrument to address the transboundary movement of hazardous waste. The Basel Convention identified dismantled ships as a significant concern as ships carry large quantities of hazardous substances. It described EOL ships as “toxic waste in disguise”. It also highlighted the environmental and health risks associated with the transboundary movement of such ships. However, the Basel Convention was initially intended for general hazardous waste, not specifically for ships. This created legal ambiguity. That is why the Hong Kong Convention (HKC) becomes more applicable and relevant today.

To directly deal with the challenges of ship recycling, the International Maritime Organisation (IMO) adopted the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (2009). The HKC is the most relevant and comprehensive set of regulations prepared so far. This convention has clear guidelines for:

- 1) Ensuring ships contain a document called the Inventory of Hazardous Materials (IHM). This document includes a list of all hazardous materials on board, along with their respective locations and quantities.
- 2) Checking and approving ship recycling yards to ensure they comply with safety and environmental regulations.
- 3) Maintaining proper handling of hazardous waste in such a way that it doesn't cause harm to the environment.
- 4) Providing proper training and equipment to the workers [6].

These agreements ensure that ship recycling does not pose unnecessary risks to human health, safety, or the environment. They also emphasise reducing the transfer of hazardous waste from developed countries to developing countries and imposing stricter safety standards at ship recycling facilities.

1.3. Safety at Ship Recycling Facilities (SRFs)

The safety of workers in Ship Recycling Facilities (SRFs) is of paramount concern as the process is highly labour-intensive and risky. Workers are exposed to various hazards, such as fires, explosions, falling from height, and asphyxiation. Furthermore, many workers lack the proper training and necessary protective equipment to mitigate these risks. About 19 fatal accidents take place on average every year in these ship recycling yards. But the number of people experiencing permanent disabilities is even higher.

In 1997, the number of deaths suddenly peaked to nearly 50 [7]. Since the 1990s, the safety of SRFs has improved, but the overall accident rate has remained alarmingly high. The fatality rate is still a significant challenge to the government and

organisations. The industry demands stricter measures and regulations for a safer working environment. **Figure 2** illustrates the number of accidents that have occurred in SRFs over the past three decades, highlighting the ongoing safety concerns.

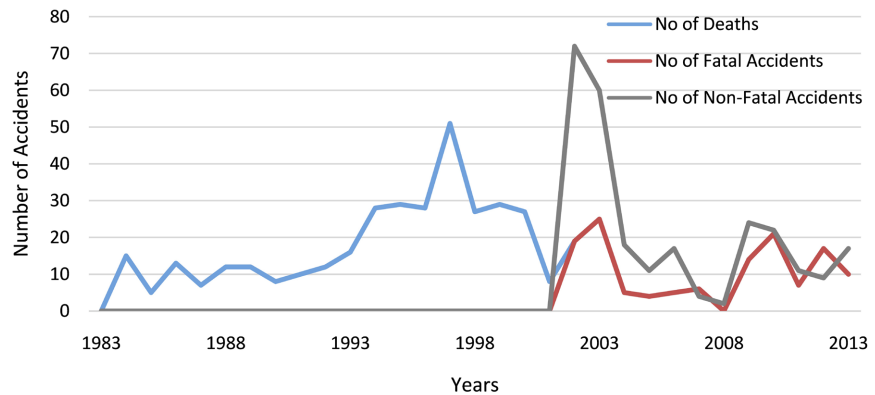


Figure 2. Ship recycling accidents in Alang [7].

Beyond these sudden accidents, workers also face long-term health problems. Continuous exposure to toxic substances and hard work in unsafe conditions may lead to severe long-term health problems. Many workers suffer from chronic respiratory diseases, skin disorders, and musculoskeletal issues. These health problems are primarily responsible for a decreased life expectancy. In Bangladesh, the average life span for workers is 40 years, which is 20 years less than the average life expectancy for Bangladeshi men [8]. Implementing a safe Ship Recycling Facility (SRF) plan with proper safety, worker training, PPEs, and strict regulations can significantly reduce risks, ultimately improving the overall well-being of the workers.

1.4. Aim and Objectives

This report aims to analyse the safety, environmental, and economic challenges of ship recycling and propose an optimised shipbreaking method which is capable of improving safety and operational efficiency. The specific objectives of this study are to:

- 1) Assess the existing challenges in ship recycling.
- 2) Identify safer and more sustainable shipbreaking techniques.
- 3) Propose an improved Ship Recycling Facility (SRF) layout that increases efficiency and worker safety.
- 4) Recommend regulations to reduce environmental risks and occupational hazards.

2. Literature Review

Several recent studies have highlighted the environmental, economic, and social aspects of ship recycling. These studies primarily cover ship recycling industries

in developing countries such as Bangladesh, India, and Pakistan, as the majority of ship dismantling is conducted in these countries.

Rahman *et al.* [9] conducted Life Cycle Assessment (LCA) of ship dismantling activities in Bangladesh. They evaluated the entire chain from transportation to domestic processing. This study emphasises the environmental benefits of recycling steel from ships and compares it to steel production from iron ores. They also mentioned how the use of gas torches poses health hazards to cutters. Therefore, the authors recommended improvements in cutting technology. They also suggested protective measures to mitigate these risks and highlighted the need for a Social Life Cycle Assessment (SLCA). In a different study, Andersen [10] adopted a systems-based approach by suggesting a Safety-Health-Environmental Concept (SHEC). The primary purpose of this approach was to better manage the risks involved in ship recycling. He divided ship dismantling activities into several categories and recommended creating detailed lists of safety rules. Important points include precautionary measures, organising the recycling facility properly, and following safe working methods. The SHEC model is meant to help countries build safer and more organised ship recycling systems.

In another study, Sujauddin *et al.* [11] focused on the material flow analysis (MFA) of steel in Bangladesh. It portrayed that the country is heavily dependent on the ship breaking industry (SBI) to fulfil its steel demand. Their primary data collection and analysis confirmed that many yards are beginning to abide by the International Maritime Organisation's (IMO) 2009 guidelines. The authors expressed optimism that Bangladesh's SBI has the potential to evolve into a sustainable sector, both economically and environmentally.

Tola *et al.* [12] explored how ideas from the circular economy can be used in ship recycling. They suggested creating a "green market" by better managing the reuse of materials taken from old ships. Their study highlights that ship recycling still falls short of adhering to circular economy models. Still, there's a big opportunity to make progress through plans like the European Green Deal. They believe that real change will require teamwork from all key players, including governments, shipowners, non-profit organisations, and recycling companies. The authors also emphasised the importance of hands-on research that looks at different areas and works across various fields to find effective local solutions.

Watkinson [13] conducted a detailed case study aimed at developing compliant models for ship recycling facilities in line with both the Basel Convention (1989) and the Hong Kong Convention (2009). This study identified short-, medium-, and long-term actions required for environmental compliance, focusing on the beaching method. This study recommended several infrastructure improvements, such as impermeable storage surfaces, engineered landfills for asbestos, and incineration for PCBs and ozone-depleting substances. This study also emphasised that compliance with the Hong Kong Convention demands additional structural and procedural reforms than those required for Basel.

Another study for a Green Ship Recycle Yard in Indonesia [14] proposed a

modern and environmentally friendly facility. This particular SRF was capable of dismantling ships up to 30,000 DWT. The yard was planned to be compliant with IMO standards and all other regulations. The proposed model is intended to prevent the release of hazardous waste into land and sea. The model ensured this through careful planning of layout and facility design. This project demonstrates that developing nations are actively developing ship recycling infrastructure on a daily basis, while also adhering to regulations.

Recent studies include a study by Misaal *et al.* [15], which is a study conducted on Bangladesh's ship recycling industry in the context of the HKC. The authors identified the challenges of implementing HKC. They also provided recommendations for improving safety by providing training, regular health assessment and financial support. In another recent study, Elizabeth *et al.* [16] investigated the requirements for handling waste and hazardous materials in green ship recycling facilities in Indonesia. This study emphasised proper ship recycling planning and proper identification of wastes. Indonesia's ship recycling industry is lagging behind primarily due to a lack of compliance with regulations. This research will be helpful for Indonesia to align with HKC and ensure the yards turn into green ship recycling facilities. ElMenshawy *et al.* [17] also presented a systematic review of the ship recycling industry. The authors mentioned how a circular economy can pave the path towards greener ship recycling.

Collectively, these studies offer a comprehensive and diverse perspective on the challenges and opportunities in the ship recycling industry. This includes the necessity for improved efficiency, worker safety and regulatory frameworks. Economic and social aspects have always been the primary focus. But these studies present a stronger push to include environmental concerns and worker safety to make ship recycling more sustainable worldwide.

3. Methodology

This study utilises a comprehensive methodology that combines literature review, structural and process analysis, economic feasibility assessments, and simulation modelling using FlexSim. Structural evaluations focus on understanding stress and failure modes in ship components. Operational strategies consider cost, safety, and environmental implications, and layout designs are tested through simulation.

This study also uses data from secondary but reliable sources, such as published papers, scientific articles, regulations, newspapers, and organisational reports. Using the FlexSim software, several internal and external parameters of the ship recycling yards are investigated. This analysis will help assess the feasibility of the current ship recycling process.

4. Structural and Operational Factors in Ship Recycling

4.1. Recycling of Materials

During ship recycling, various materials are recovered, not just steel. These scrap

materials are generally classified into two main categories: ferrous materials and non-ferrous materials. Ferrous materials, which primarily consist of steel, make up the majority of the total recoverable content from a vessel. **Table 2** presents the product breakdown from ship recycling, indicating the estimated proportions by weight for various ship types.

Table 2. Product breakdown from ship recycling.

Types of Recovered Products	Oil Tankers	Bulk Carriers	General Cargo and Cruise Ships
Ferrous Metals	86%	82%	77%
Non-Ferrous Metals	1%	1%	1%
Furniture	2%	3%	4%
Machinery	3%	5%	6%
Waste	8%	9%	12%

4.1.1. Ferrous Materials

Ferrous materials are the most significant component in ship recycling operations due to their higher proportion and extensive reuse potential. Ferrous materials primarily consist of steel. As a result, recycling steel from decommissioned ships significantly reduces the demand for iron ore mining, helping to preserve the environment. This practice is especially impactful in developing countries such as Bangladesh and India, as it curtails the need for steel imports and helps in saving substantial foreign currency. This is more important in Bangladesh as the country lacks natural iron ore reserves. **Figure 3** illustrates the typical flow of the steel scrap industry in Bangladesh.

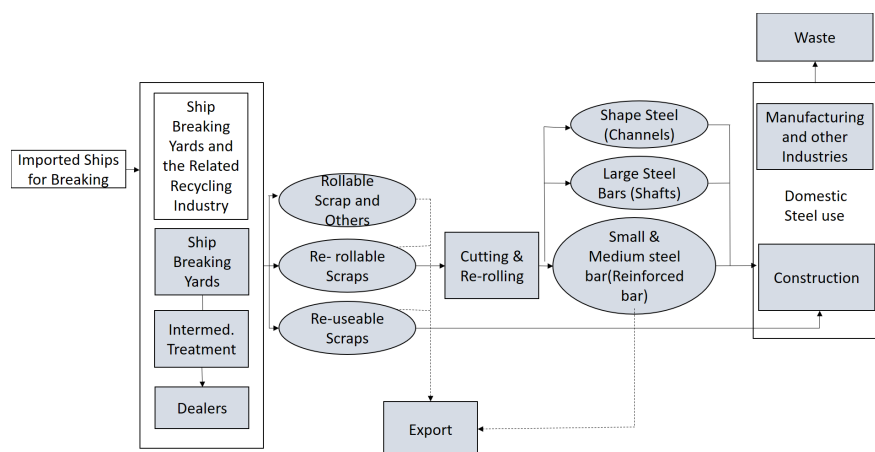


Figure 3. Flow of steel scrap in bangladesh.

Over 70% of a ship's deadweight consists of steel. Thus, dismantling a mid-sized tanker of around 25,000 DWT can yield approximately 17,500 tonnes of recyclable steel. The cumulative effect of such recycling efforts results in significant savings of natural resources. **Figure 4** presents the global gross tonnage of scrapped ships.

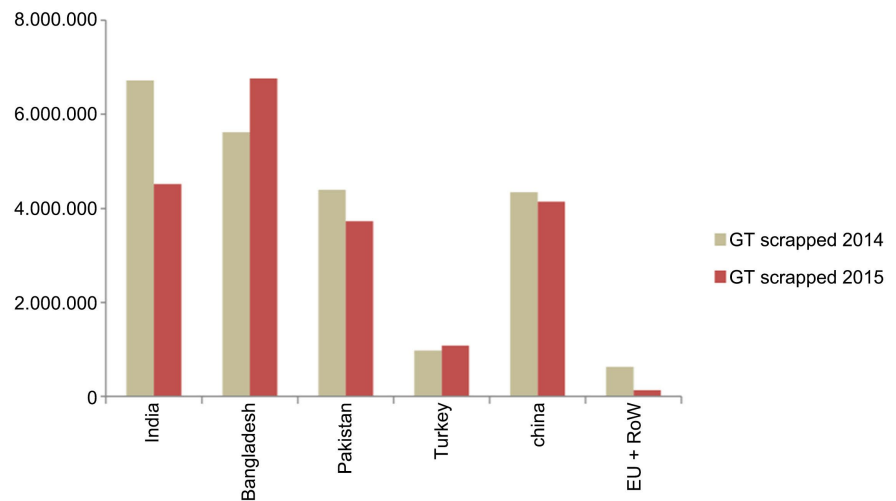


Figure 4. Gross tonnage of ships scrapped globally [18].

Metal cutting during ship recycling is primarily performed using two methods: Gas-Torch Cutting and Shearing. Cutting these massive ship structures into smaller pieces can be extremely risky. Improper or unplanned cutting may even lead to the collapse of the ship structure, which is one of the leading causes of accidents in Ship Recycling Facilities (SRFs). In developed countries, SRFs typically rely on shearing as the primary method to dismantle the ship's structure before proceeding to gas-torch cutting. This approach often results in a significant reduction in the value of a substantial portion of the recovered scrap.

1) Gas-Torch Cutting: This is a widely preferred method for cutting metal. It uses gas-fuelled torches, such as propane, butane, acetylene, natural gas, or fuel gas, to generate the high temperatures required for cutting metals. Torch cutting is favoured because it allows large steel plates to be cut to specific dimensions without requiring re-rolling mills or re-melting furnaces, resulting in substantial cost and time savings.

2) Shearing: Shearing involves using large industrial shears, particularly in more developed SRFs. These shears are primarily utilised to dismantle non-ferrous metals and effectively reduce large metal parts into smaller sizes for remelting. Shearing is faster and less labour-intensive than torch cutting, making it attractive in high-capacity facilities. However, it comes with high capital costs, and the scrap produced must be remelted before it can be processed into usable steel products, making it less efficient than gas-torch cutting in terms of value retention.

Studies conducted in Bangladesh indicate that the country required around 2,930,000 tonnes of steel for domestic consumption in 2010, of which 71% was in the form of bars [11]. Re-rollable scraps—typically larger than 10 cm in width and elongated—are directly collected and processed into finished steel products, eliminating the need for energy-intensive re-melting. As a result, gas-torch cutting plays a crucial role in maximising the value of scrap material. **Table 3** provides an overview of domestic scrap consumption in Bangladesh.

Table 3. Domestic scrap consumption in bangladesh.

Total Domestic Consumption 2930	Unit: 1000 tonnes	
	Products	Sectors
	Rebar 1839	Other Industries and Consumers
	Plate 676	710 - 1091
	Other Bar & Shape Steel 381	Construction 1839 - 2220
	Pipe 34	

4.1.2. Non-Ferrous Materials

Ferrous materials are abundantly recovered during ship recycling. However, as illustrated in **Figure 5**, non-ferrous metal scraps hold significantly higher value than steel [19]. Non-ferrous metals such as copper and aluminium are among the valuable materials extracted during dismantling.

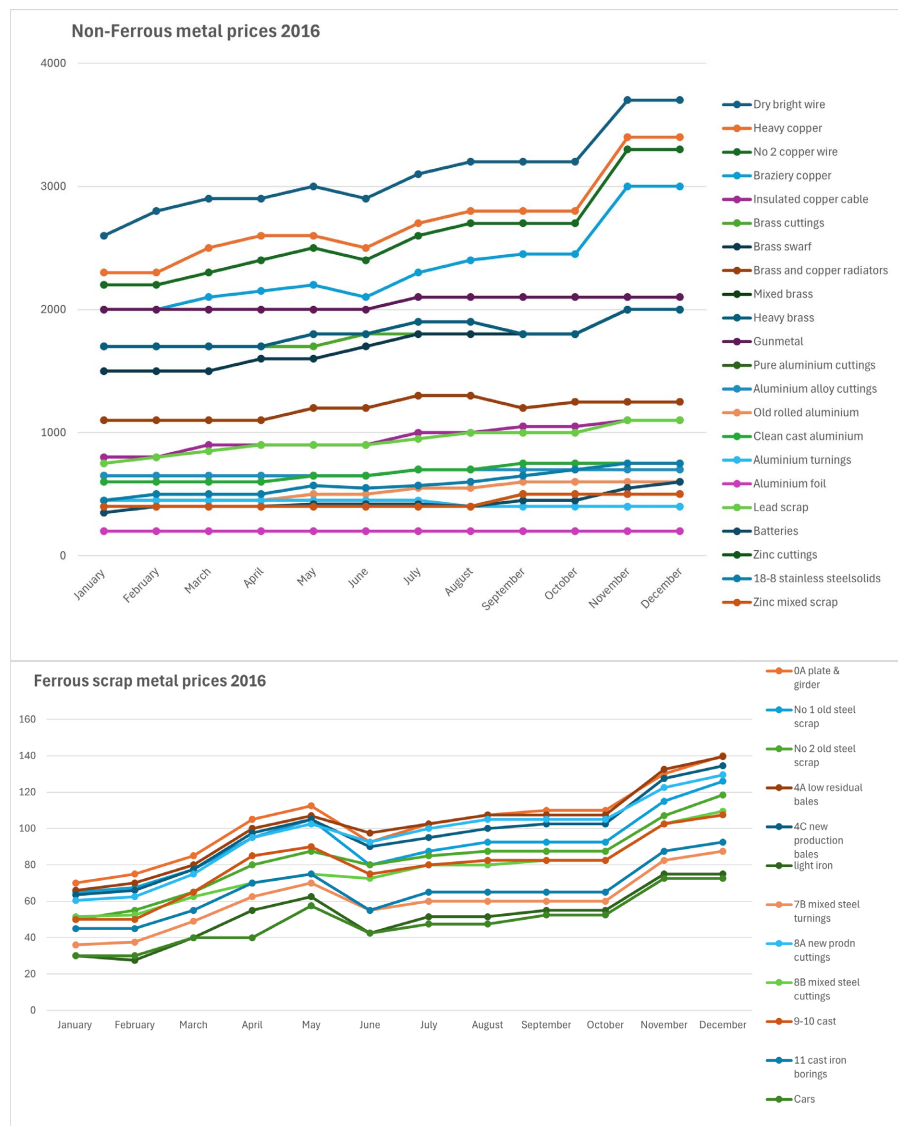
**Figure 5.** Comparison between ferrous and non-ferrous scrap prices [19].

Table 4. Recoverable materials weight data (Percentage of LSW) [20].

Type of Vessel	Reroll Scrap	Melting Scrap	Cast Iron	Non-ferrous Metals	Machinery	Furniture and Misc.	Weight Lost
General cargo	56 - 70	10	2 - 5	1	4 - 8	5	9 - 15
Bulk carrier	61 - 71	8 - 10	2 - 3	1	2 - 5	1 - 5	10 - 16
Ore carrier	62 - 69	10	3	1	3 - 5	5	10 - 16
Passenger	44 - 58	10	5	1 - 2	10 - 15	5 - 7	11 - 17
Oil tanker	72 - 81	5 - 7	2 - 3	1 - 2	1 - 2	5	10 - 12
Ore carrier	66 - 75	8 - 10	3	1	1 - 6	1 - 2	10 - 13
Naval ship	53 - 67	10	2 - 6	1 - 2	4 - 6	1 - 2	15 - 22
Container ship	63 - 67	10	3 - 4	1	5	5	10 - 13
Fishing vessel	47 - 67	10	3 - 8	1 - 2	2 - 10	5	12 - 18
Average	64	9	4	1	5	4	13

Among all the vessels, tankers, cruise, and naval vessels typically have more non-ferrous scrap compared to other ships (Table 4). This is due to the extensive use of copper in steam lines (for heating cargo) and electrical wiring (for passenger comfort or sensitive equipment), which have high scrap value. Table 4 shows the typical scrap weight breakdown across different vessel types.

4.2. Structural Integrity and Failure Risks

While dismantling a ship, assessing its structural integrity is crucial to prevent accidents involving workers. Understanding the types of stresses and potential failure modes of the ship's structure is essential. The stress components are categorised as:

- 1) **Primary Stresses:** These are generated primarily by hull girder bending. Can be calculated using beam theory and considering horizontal and vertical bending moments (BM)
- 2) **Secondary Stresses:** These arise mainly from local loads in individual tanks and cause bending in large stiffened panels between bulkheads.
- 3) **Tertiary Stresses:** These occur from local bending between stiffeners and are calculated using classic plate theory.

The main failure concerns during ship dismantling are yielding and buckling, caused by bending moments (BM) and shear forces. These factors must be evaluated during the survey and pre-planning phase to ensure safe dismantling.

5. Innovative Ship Recycling Concepts

Innovative dismantling strategies must be considered to develop safer and more efficient ship recycling yards. Traditional beaching methods have raised concerns about worker safety and environmental pollution. Van [5] proposed two alternative methods to address these issues: the Early Vessel Separation (EVS) concept and the Stage-wise Dismantling System (SWS). However, combining these approaches into a new hybrid model can further enhance safety, efficiency, and environmental compliance.

5.1. Early Vessel Separation (EVS) Concept

The EVS concept involves using a Floating Dock (FD) to support the aft section of the ship, where the engine room is located [5]. While afloat, the ship is cut transversely (as shown in **Figure 6**). This separates the forward cargo-carrying section from the aft and also minimises pollution risk as machinery spaces and fuel systems are isolated and managed in a controlled environment. All fuel oil, lubricants, and oily wastes are pre-emptively removed and sent to certified oil reception facilities. This process significantly reduces the risk of environmental contamination and ensures safer working conditions due to the controlled dismantling environment provided by the FD.

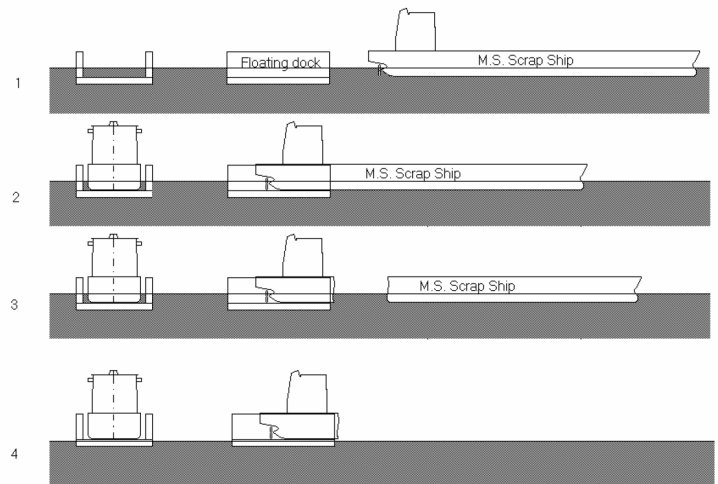


Figure 6. Early vessel separation [5].

5.2. Stage-Wise Dismantling System (SWS) Concept

In the SWS approach, dismantling is carried out sequentially at a jetty or dock, as demonstrated in **Figure 7**. Initially, deckhouses and the engine room are dismantled into large blocks (20 - 30 tonnes) and transported to processing yards. The remaining steel hulls are later moved to a beaching site for further breakdown.

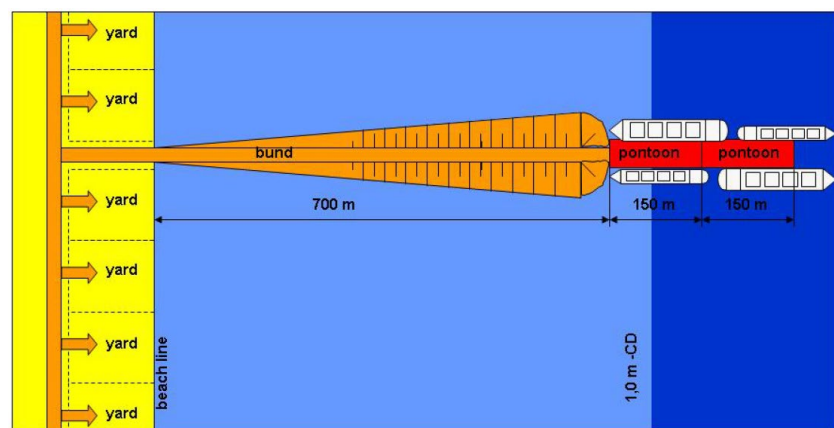


Figure 7. Stage-wise dismantling facility [5].

5.3. Combination Concept

A combination concept is proposed to maximise the strengths of EVS and SWS while addressing their limitations. The process begins with the vessel's segmentation using an FD, separating the forward and aft sections. The FD, with the aft part, is moved to a quayside yard, where the superstructure is removed for cleaning and dismantling. This enables cranes and other equipment to lift heavy machinery out of the ship. **Figure 8** represents the workflow associated with the Combination Concept.

After the ship is separated into two parts, the crane machinery enters the engine room and the forward hull. The FD is shifted to a quayside yard. Once brought to the quayside, the superstructure can be removed while a more thorough cleaning is done in the machinery spaces. The removal of the superstructure will free the deck, allowing a crane to be removed from the ship.

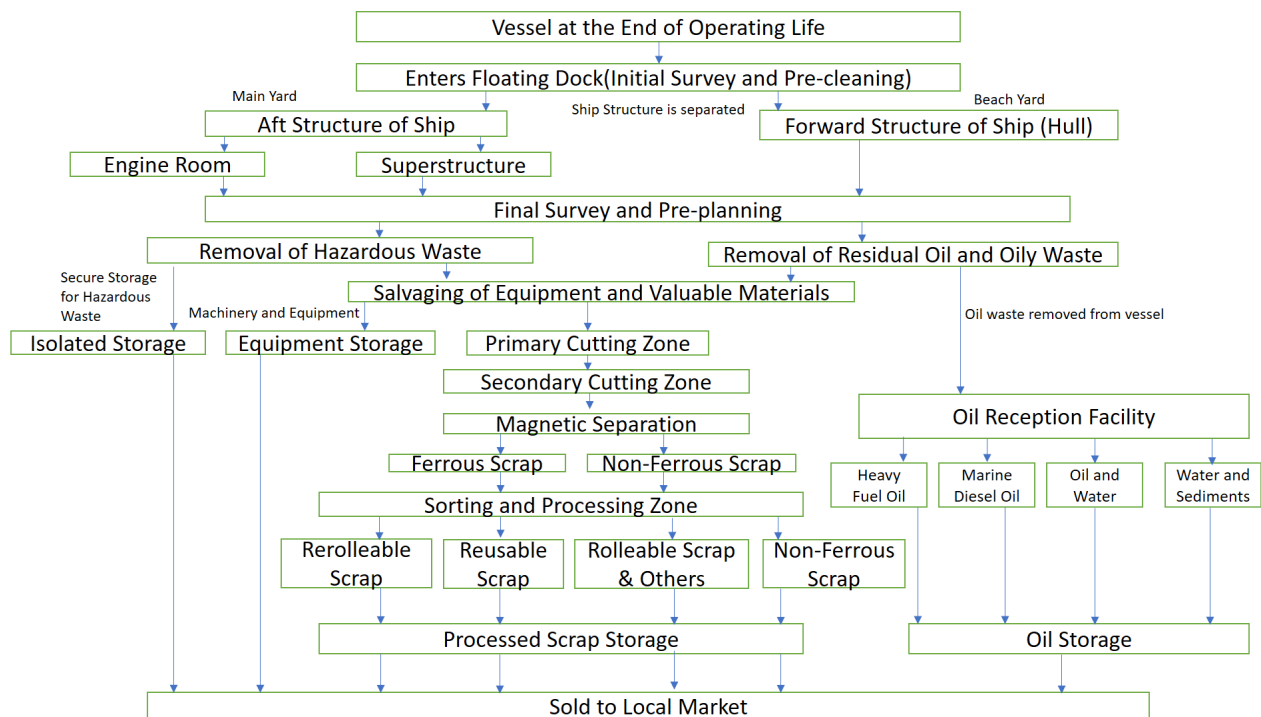


Figure 8. Combination Concept Workflow.

The superstructure will then be transported to another area to be dismantled via a floating barge or after being cut into large transportable blocks. Metal scraps obtained from the superstructure are referred to as reusable scraps and are 100% recycled in the market. Thus, it is vital to ensure that the superstructure is transported appropriately so that its metal condition remains intact. At the same time, the safety of valuable equipment in the deckhouse is also ensured. Most of the pollutants are located in the aft part and, hence, require more safety measures and the facilities of a yard to contain them. Heavy machinery and valuable equipment also require cranes to remove them while maintaining them in working conditions.

to be sold to achieve better market prices.

As the forward part of the ship consists of the cargo holds and tanks, it is mainly made of steel. Hence, this part is beached for cutting while the aft part is dismantled in the FD. This forward part is brought to the beach by tugs and dragged in by the winches. The ship structure will not be partially floating or grounded on the beach. This is an additional safety factor as there is no bending moment when the vessel is thoroughly grounded. For a bending moment to exist, there is a need for shear force. However, since the structure is wholly grounded, there is no load difference between the structure's weight and the buoyancy force. Thus, there is greater safety for the workers as there are fewer concerns about structural failure due to the bending moment.

The forward part, which is beached along the coast, is cut apart using the cutting concept stated below, while supported by mechanised and adequate facilities, such as forklifts and winches. Scraps cut from the structure should be done using a gas torch, cutting to achieve the desired scrap dimensions suitable for immediate use or recycling processes such as rebar or re-melting.

These three dismantling processes can be carried out concurrently, each having its relevant appropriate facilities and safeguards.

5.4. Concept Comparison

Each of the proposed ship recycling concepts, EVS, SWS, and the Combination Concept, has distinct advantages and disadvantages, depending on the specific needs and goals of the ship recycling yard. A comparison of these methods reveals their respective strengths and limitations:

1) EVS is the safest method regarding worker safety and environmental impact, but it requires a significant initial investment in floating docks and associated infrastructure, which can reduce profit margins.

2) SWS is more cost-effective. It also requires less space, allowing multiple vessels to be processed simultaneously. However, it does not provide the same level of safety or pollution control as EVS. This means that this process may lead to environmental concerns and an increased risk for workers.

3) The Combination Concept strikes a balance between the safety of EVS and the space efficiency of SWS. This concept enables the simultaneous disassembly of the vessel's components. As a result, the time required for the recycling process is reduced significantly. Although the initial investment is slightly higher, the long-term benefits make it a worthwhile investment.

In conclusion, the Combination Concept provides the most comprehensive and balanced solution for developing safer and more efficient ship recycling yards. By combining the best features of EVS and SWS, this approach improves the overall efficiency of the recycling process. Besides, this also enhances safety standards and minimises environmental impact. **Table 5** illustrates how this concept represents a more sustainable, effective, and economically feasible approach to ship recycling.

Table 5. Comparison of EVS, SWS, and combination concept.

Feature	EVS	SWS	Combination Concept
Safety	High	Moderate	High
Environmental Risk	Low	Moderate	Low
Initial Investment	High	Moderate	Moderate-High
Efficiency	Moderate	High	Very High
Structural Risk (During Cutting)	Low	Moderate	Low
Profit Margin	Low-Moderate	High	High (Long-Term)

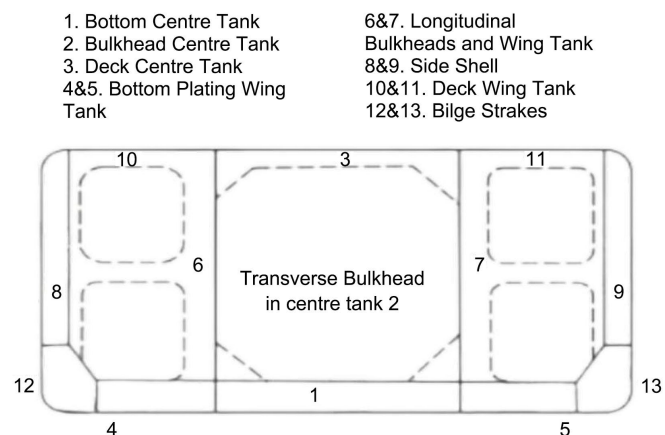
5.5. Cutting Concept

The cutting process will differ for each vessel type due to its different general structure. Currently, the industry lacks a standardised framework or sequence for recycling and disassembling ships. Thus, for this study, the double hull of a tanker is used as the template.

Since the vessel is wholly beached, the simple beam theory is applied to study the forces acting on the structure, but there is a negligible bending moment. When the structure is beached, there is almost no difference between the lightship weight of the vessel and the buoyancy force. Therefore, a negligible shear force is acting on the ship, and hence, there is no bending moment. The negligible shear force and bending moment arise from the soil mechanics for the beach. This is due to the water permeating within the soil or sand of the beach, resulting in a slight buoyancy force acting on the structure. Since the aft part of the vessel has been removed, the general arrangement of the cargo holds in the forward section is generally the same.

The keel plate, which runs along the entire length of the vessel, supports the framework and therefore resists most of the longitudinal stresses. Thus, it is crucial to leave the keel blocks for last during the dismantling process.

Tankers with a double bottom and hull require a structurally sound inner structure, in case of any collision or damage to the outer shell. Hence, the outer shell should be removed first while dismantling the vessel. The sequence of cutting the shell should be in the reverse order from what is shown in **Figure 9**.

**Figure 9.** The sequence of ship cutting in reverse order.

This cutting concept is proposed because there have been too many accidents or deaths of workers on board the vessel due to asphyxiation, fires and explosions. Removal of the outer shell exposes the interior of the ship, facilitating access to the structure and providing ventilation to the workspace. Using cranes or winches, materials or equipment can also be brought onto or removed from the vessel via these new entry points.

Materials or equipment can also be brought onto or removed from the vessel via these new entry points using cranes or winches. Thus, this method considers not only the workers' safety but also the economy and efficiency of the work process. Scraps cut in this layout across the vessel's length are more desired by the scrap market. As a result, the scrap becomes more valuable in the scrap market.

The cutting sequence proposed above is specifically dedicated to double-hull tankers. Still, some of the basic principles like removing outer shells first for safety can be generalised and applied to other ships too. However, ships of other types require customisation due to differences in general arrangements. More research should be done for designing a dedicated sequence for each type of ship.

6. SRF Infrastructure Design

Based on the new Combination Concept proposed, a new SRF design is developed to address the safety, environmental and efficiency issues of the current ship recycling process. However, this new design emphasises trying to minimise initial investment while addressing these issues.

6.1. Design Considerations

An SRF should also have many basic infrastructures to facilitate ship recycling, but the crucial facilities required in developing countries can be summarised into the following two sections:

6.1.1. Infrastructure

- 1) Winches: To facilitate the removal of materials and the dragging of the ship structure inland.
- 2) Hazardous waste storage: Specified isolated storage areas for hazardous waste.
- 3) Oil reception facility: This facility separates usable oil and resells it back to the market, using underground pipelines to ensure it is not exposed to the surface and to prevent accidental leakage.
- 4) Emergency service units: For ensuring an immediate response.
- 5) Secure containment system: For preventing pollution resulting from spillages during the dismantling of the ship.
- 6) Floating docks (FD): To accommodate the aft structure of the vessel for the ease of transport and manoeuvrability. It can relocate to other central yards to meet demand, rather than having a permanent structure. FD is also used because it can be built to the required size. Additionally, since it only accommodates the

aft of the vessel, it can be built to an optimum size, rather than creating a large one that is not fully utilised. Hence, lowering initial investments.

7) Cranes: Cranes with sufficient height and carrying capacity are available to lift the superstructure from the vessel's aft structure. These cranes can also be used to ensure the equipment is not damaged during extraction and for the safety of the workers.

8) Workshops: For allowing cutting to take place under all weather conditions.

9) Magnetic separation facilities: These facilities easily separate non-ferrous scrap from ferrous materials, minimising the wastage of steel fluff.

10) Transport infrastructure: The facility should have basic road infrastructure to facilitate the movement of heavy materials in and out of it.

11) Machinery Storage: A storage area for machinery and equipment before they are sold to the local market.

6.1.2. Location and Capacity

1) The SRF should be located in coastal areas that allow it to receive vessels regardless of weather conditions.

2) There should not be any capacity restrictions to accommodate large vessels.

3) Needs to be reasonably easy to access via public transport or near an airport for clients or inspection parties for quality checks.

6.2. Proposed Layout of SRF

This proposed layout can be divided into two segments: the Main yard and the Beach yard. A simulation and modelling of this workflow process and this layout concept have been done using FlexSim and are attached in a separate document.

6.2.1. Main Yard

The main yard layout, as shown in **Figure 10** (The simulation model was developed using FlexSim (FlexSim Software Products, Inc.)), is divided into five zones:

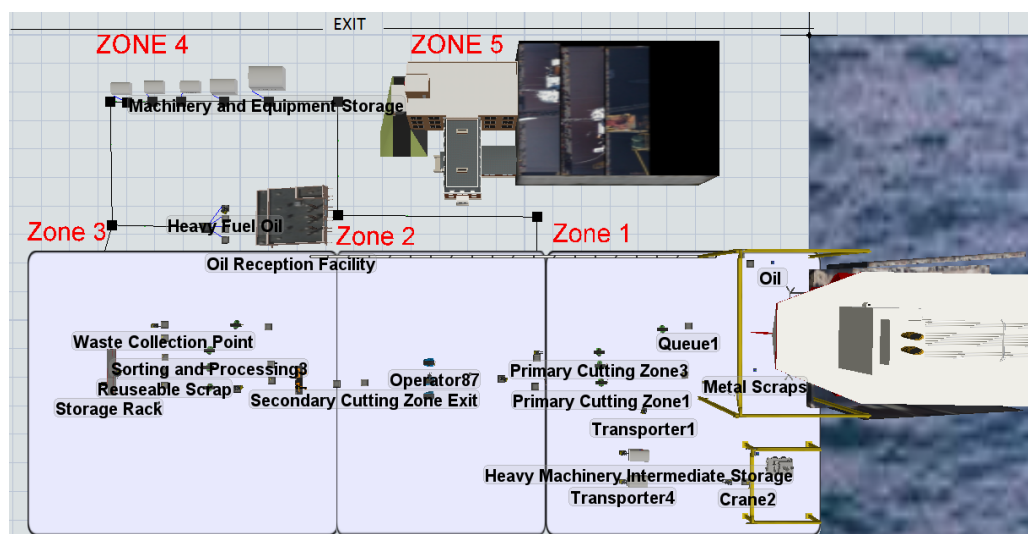


Figure 10. Layout of main yard [Source: FlexSim Simulation].

- 1) Zone 1: Primary Cutting
- 2) Zone 2: Secondary Cutting
- 3) Zone 3: Processing and Sorting
- 4) Zone 4: Storage and Waste Collection
- 5) Zone 5: Emergency Facilities and Office

When the aft structure of the vessel is docked in the FD, pre-planning and survey will be immediately carried out to provide the yard with a good understanding of the conditions onboard the structure, enabling the allocation of proper manpower and equipment for work. Then, the hazardous waste is removed. The residual oil and oily waste are also pumped out into the Oil Reception Facility, where they are sorted into Heavy Fuel Oil, Marine Diesel Oil, Oily Water, and Water with Sediments. The residual oil can then be sold in the local market to generate additional profits.

The superstructure is then cut up and removed, exposing the main deck. The deck can then be cut to reveal the engine room, facilitating the removal of valuable equipment and materials. The equipment and machinery extracted will then be stored in the warehouse, awaiting purchase by potential buyers. The superstructure and the main body can then be cut down simultaneously to increase the efficiency of the recycling process.

Zone 1 will then cut the structure into large blocks and transport them to the primary cutting workshop, where they can be further cut down into smaller blocks. These blocks will then be cut down further into plates in Zone 2 before being sent to Zone 3, where they will be sorted into ferrous and non-ferrous scrap materials using a magnetic separator. The sorted materials will then be cut into the desired shapes and sizes and sorted accordingly before being sent to the storage warehouse in Zone 4. The storage area in Zone 4 will encompass the Oil Reception Facility, Hazardous Materials Storage, Waste Collection Facility, Oil Storage, Processed Materials Warehouse and the Machinery and Equipment Warehouse. Zone 5 includes the office and emergency services. The office is situated near the FD and the exit, allowing for better management and supervision of the ship recycling process.

6.2.2. Beach Yard

This yard is divided into the Ship Dismantling Area and the Cutting and Processing Area (see **Figure 11**). The simulation model was developed using FlexSim (FlexSim Software Products, Inc.). The forward structure of the vessel is beached with the help of tugs and then pulled inland using winches. Once the ship is fully beached, the survey, pre-planning, and removal of hazardous materials and valuable equipment must be carried out before the ship is recycled.

The cutting concept, as mentioned above, will be used to disassemble the structure, and these plates on the ship's shell can be removed with the assistance of the winches. During this time, alarms will be sounded to alert workers that no one will be in the danger zone where falling objects may be present. These large plates are then drawn inwards by the winches and brought into the primary cutting zone,

where they are cut down into smaller pieces before being processed, sorted, and then transported to the main yard for storage. The cutting process in the beach yard is similar to that in the main yard, but is more manpower-centric to reduce the initial investment cost. However, crucial processes that significantly affect workers' safety and impact the efficiency of the recycling process will have their relevant equipment provided. One such example is the use of winches and forklifts for heavy lifting.

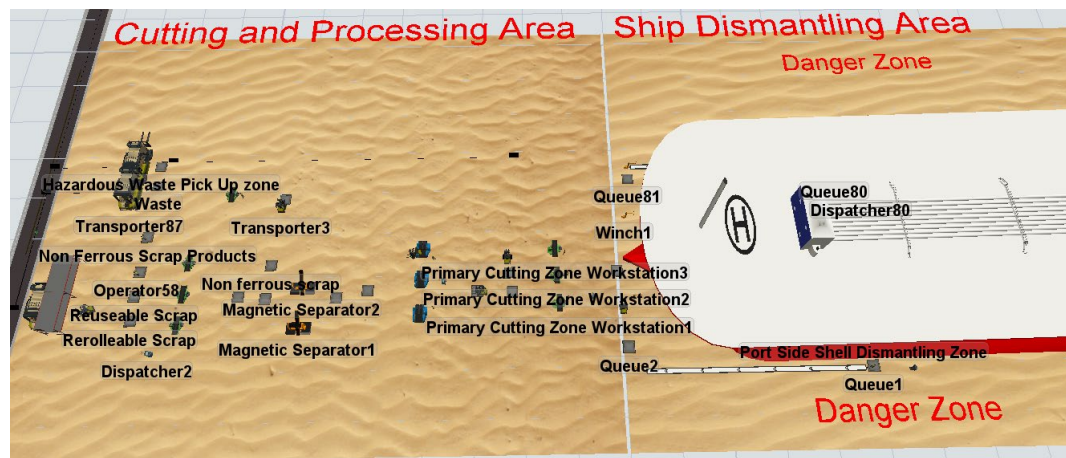


Figure 11. Layout of beach yard [Source: FlexSim Simulation].

7. Results and Discussion

The proposed Combination Concept for recycling was formed by incorporating the Early Vessel Separation (EVS) and Stage-wise Dismantling System (SWS). It has been simulated and evaluated using FlexSim. It demonstrated notable improvements in safety, operational efficiency, and compliance with environmental regulations. The operation time was reduced by simultaneous work and process optimisation across both the main and beach yards.

This study reveals that current ship recycling methods, especially the beaching method, carry significant risks. Risks include structural failures during cutting and environmental hazards from oil and toxic materials. These are addressed systematically in this study by introducing the concept of combination. For instance, using floating docks for aft dismantling ensures that the machinery zone is handled in a way that minimises oil leakage and accident rates.

The new SRF layout was divided into the Main and Beach Yard. The feasibility of dividing into segments was verified by simulation. The Main Yard was structured into dedicated zones (cutting, sorting, storage), which provided a smoother workflow and improved material handling. At the same time, the Beach Yard supports manual operations. Instead of relying entirely on manual labour, it also includes necessary automation, such as winches and forklifts.

Additionally, the proposed cutting sequence for tankers prioritises worker safety. In this sequence, the outer shell is removed first to reduce the chances of asphyxiation and structural failure. This sequence also contributes to producing dimensionally appropriate scraps, which are highly valued in the market.

Overall, the study's results strongly support the feasibility of implementing these ideas. Though they involve a moderately higher initial investment, the long-term gains in profit margins, safety and regulatory compliance outweigh the costs.

8. Recommendations

The entire ship recycling process can be improved by properly tackling the existing challenges. Here are some recommendations which can be useful in upgrading the ship recycling industry in terms of safety and environmental impact:

8.1. Implementing the Combination Concept

Ship Recycling Facilities (SRFs) need to make full use of the combination concept. This concept maximises the business's potential by offering a high profit margin. It also has higher efficiency than EVS and SWS methods. The only downside of this concept is that it takes longer than EVS and SWS in capital recovery. On the other hand, most yard owners expect to receive immediate returns. If yard owners can trust the method and be patient, it will provide a better output in terms of profit in the long run.

8.2. Maintaining Proper Cutting Sequences

Different types of ships have different general arrangements. As a result, the cutting process and sequence vary too. For example, it is more appropriate to remove the outer shell first for tanker ships. Taking this step first relieves the workers from the risk of asphyxiation. Besides, this also reduces the chances of accidents occurring due to structural failures. Currently, the ship recycling industry lacks guidance on the cutting sequence. As a result, the cutters cut the ship in random order and accidents take place. Naval architects can help by creating proper cutting sequences for different ship types. After the sequences are prepared, cutters will be able to follow and maintain appropriate sequences, thus achieving better output.

8.3. Segmented SRF Layout

The existing yards can be divided into two segments, the Main Yard and the Beach Yard. Beach Yard can be used for cutting large sections of the ship right after it enters the yard. The Main Yard can be utilised for taking apart smaller parts and sorting materials. This will allow dismantling to occur simultaneously at two locations. Apart from that, the material handling will become smoother, and overall efficiency will increase.

8.4. Investing in Necessary Yard Equipment

Shipyards can consider investing in infrastructural development to ensure a safer yard. If a yard is well equipped, it becomes much easier to minimise the number and severity of accidents. For example, having cranes with enough lifting capacity can reduce the risk of objects falling from a height. Again, winches decrease the possibility of hitting a worker's foot while dragging ship sections to the

yard. Magnetic separators make sure that ferrous and non-ferrous materials are correctly distinguished. If sorting is done manually, there is a chance that the items will get mixed together. Therefore, for the sake of a safer and more efficient yard, SRFS need to ensure the availability of cranes, floating docks, magnetic separators, emergency service units, and oil reception systems.

8.5. Monitoring Regulations

There is no alternative to implementing regulations for proper waste disposal systems and worker safety. From past experiences, it is evident that creating a regulated work system in yards is difficult. Providing mere regulations and expecting them to be followed by workers and yard owners is unrealistic. Instead, a system can be created in which the relevant party is rewarded or penalised based on their actions. Yard owners and workers who follow safety rules will receive rewards. At the same time, upon violating the rules, strict penalties such as fines or legal actions will be imposed. A third-party organisation can implement this system to maintain regularity and transparency.

8.6. Training and Worker Safety Programmes

Most accidents in the ship recycling industry take place due to a lack of awareness and careless handling of hazardous materials. Therefore, investing solely in machinery is insufficient until a sufficient number of trained workers are available. Arranging regular safety drills, training, and workshops conducted by experts will enable the worker to become more skilled and aware. Most of the workers received little or no formal education. So, training should be structured in such a way that even workers who are unable to read or write can understand and grasp the training lessons. Besides decreasing accident rates, these trainings will also uplift workers' confidence.

8.7. Research and Development

The infinite potential of ship recycling industry is being constrained by its environmental effect. It is even possible to reduce environmental impact without making any changes to the yard. If a suitable location is chosen, it will mitigate the impact to some extent. So, selecting appropriate locations for yards can be considered a potential area of research. Several factors need to be considered when choosing a location, such as proximity to international routes, availability of skilled labour, and ease of access to the yard. Apart from its strategic location, further research and development should also be conducted on the practical method of dismantling the superstructure.

8.8. Public-Private Partnerships (PPPs)

Most of the time, governments are capable of providing policy and regulatory support, but a lack of budget remains. Public-Private Partnerships (PPPs) offer a solution to this budget constraint faced by the government. This will also reassure

the safety of the investment as the government is a trusted authority. The private sector can provide capital and technical expertise, which can be utilised in infrastructural and technological improvements. Mutual effort between the government and the private industry will accelerate the yard modernisation process.

Implementing these recommendations simultaneously will be challenging. But with proper planning and support, each of them is achievable. The authority should implement the recommendations by starting with the most important first and later ones in accordance with the priority. Over time, the industry is expected to evolve into a greener and more sustainable sector.

9. Conclusions

Ship recycling is one of the most critical industries for handling EOL (End of Life) ships. Despite having a significant role in recovering reusable materials, recycling usually receives far less attention than ship design and remains overlooked. However, it is essential to have a safer recycling yard for the betterment of the environment, workers, and the industry's sustainability.

The current study presents a more effective and safer method for recycling old ships by combining two innovative ideas. The new Combination Concept was introduced by combining Early Vessel Separation (EVS) and Stage-Wise Dismantling System (SWS). The Combination Concept helps reduce the chances of accidents, protects the environment, and makes the recycling process more organised. It mainly focuses on safely removing dangerous materials and machinery from ships.

A new layout for ship recycling yards was also designed to coordinate with the concept of combination. In this new layout, SRF is divided into Main Yard and Beach Yard. Main Yard is used for cutting and sorting scrap, and the Beach Yard is utilised by bringing ships for beaching, pre-planning, and removing hazardous materials. Simulation using FlexSim showed that this layout can make the workflow smoother, faster and safer.

In the future, more research should focus on dismantling the superstructure and developing a cutting sequence. Apart from these, the selection of the location of new yards can also be investigated. The solution to a safer and more sustainable ship recycling industry lies in innovative and well-researched methods, as well as their practical implementation.

This new model of recycling process will enable the ship recycling industry of South Asian countries to keep pace with the rest of the world and stay competitive in the market. Implementing this new model can pave the path towards attracting more business due to enhanced safety and efficiency. Bangladesh has the potential to implement innovative recycling models, such as the one mentioned in this study, which can help it maintain its leadership in the global market.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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