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Designing Efficient and Contemporary Ship Recycling Yards through Discrete Event Simulation

by

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ABSTRACT

Ship recycling, similar to any other recycling industry, can be considered as the most environmentally friendly option for end-of-life ships than the other alternatives. However, lack of safety, lack of environmental awareness as well as lack of a global and local regulatory framework resulted in ships being dismantled in undesirable conditions which forced international regulators to focus on developing international regulations and standards. The International Maritime Organization’s (IMO) Hong Kong Convention and the European Union’s Ship Recycling Regulation are examples of the aforementioned new regulations. Both regulations require ship recycling yards to improve existing HSE standards to stay compliant. These HSE measures will negatively impact on running costs, therefore, ship recycling yards will need to increase their production efficiency to remain competitive.

Even though the industry requires support during this transition, there is no study within the current body of literature that focuses on increasing the productivity of the ship recycling facilities. Hence, there is a need to develop a framework to design contemporary and efficient ship recycling yards. Increasing production efficiency in ship recycling yards will not only decrease the costs, but it will also increase the throughput of the yards which will generate more income and positively impact on overall profitability. Therefore, this PhD study addresses this gap through the development of a simulation framework for ship recycling industry to design and optimise the ship recycling yards. The study adopts a case-based approach where numerous design alternatives will be studied through the proposed framework. The main aim of this study is to increase the productivity of ship recycling yards and optimise their procedures towards achieving cost-efficient facilities.

Overall research conducted in this study will be significant contribution to the maritime literature as a novel framework for ship recycling yard design and optimisation is developed. The process models of this framework are developed based on real ship recycling procedures, therefore, the framework can be considered ready for practical implementation.

ABBREVIATIONS

BAN	Basel Action Network
BC	Basel Convention
Cd	Cadmium
CFC	ChloroFluoroCarbons
Cr	Chromium
Cu	Copper
DES	Discrete Event Simulation
DSS	Decision Support System
DWT	Deadweight Tonnage
EC	European Commission
EU	European Union
Fe	Iron
GT	Gross Tonnage
Hg	Mercury
HKC	Hong Kong Convention
HSE	Health, Safety and Environment
IHM	Inventory of Hazardous Materials
ILO	International Labour Organization
IMO	International Maritime Organization
LDT	Light Displacement Tonnage
MARPOL	International Convention for the Prevention of Pollution from Ships
Mn	Manganese
NGO	Non-Governmental Organization
ODS	Ozone Depleting Substance
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PAH	Polyaromatic Hydrocarbon
Pb	Lead
PCB	PolyChlorinated Biphenyl
PHC	Petroleum Hydrocarbons
PPE	Personal Protective Equipment
PVC	Poly Vinyl Chloride
REACH	Registration, Evaluation, Authorisation & restriction of CHemicals
SRP	Ship Recycling Plan
TBT	Tributyltin
WEEE	Waste Electric Electronic Equipment

Chapter 1 Introduction

1.1 Chapter Overview

This chapter explains the background of the ship recycling industry and summarises the study conducted.

1.2 General Perspectives

When a ship reaches its economic end-of-life, the best option for both economic and environmental reasons is recycling the ship to recover the items used on board the ship compared to other alternatives such as sinking or abandoning.

95 to 98% of the ship's material and equipment in terms of weight can be recycled (McKenna et al., 2012). The majority of a ship's weight consists of metals (ferrous and non-ferrous), and because our world is going through a metal mineral scarcity (Henckens et al., 2014), it is critical to recycle or reuse the metals when the asset is at the end of its life. Furthermore, a recent study concluded that the production of one ton of steel from hematite ore requires 7,400 MJ of energy while releasing 2,200 kg of carbon dioxide. However, compared with the values mentioned above producing the same amount of steel from scrap requires 1,350 MJ of energy and releases 280 kg of carbon dioxide (Yanmaz, 2005). Thus ship recycling, similar to any other recycling industry, can be considered as the most environmentally friendly option for end-of-life ships than the other alternatives. In addition to the metals, the used equipment on board ships can be further utilised by selling them in the second-

hand markets or directly from the yard or, through remanufacturing by the original equipment manufacturer to extend the life cycle or through recycling to reclaim the raw materials. Majority of these materials and equipment on board ships can be recycled or can be reused in for repairing/maintaining the existing ships as well (or even in different industries).

Currently, the majority of the ship recycling is executed in developing countries; India, China, Bangladesh, Pakistan, and Turkey together dismantle 99% of the total LDT (Figure 1.1) (NGO Ship Breaking Platform, 2017). Ship recycling, as an industry, contributes to economic development of these countries by supplying the material needs of the manufacturing and other industries through the materials obtained from the end of life ships. However, even though recycling the ship is the most environmentally friendly option for end of life ships considering the other options (sinking, or abandoning), it remains as a contentious issue. The ship recycling process is very complex and hazardous work if not done correctly (ILO, 2004). Ship recycling involves a wide range of activities and operations which may expose workers to hazardous situations resulting in incidents, accidents health problems, injuries and even fatalities (OSHA, 2010). Also, due to the toxic wastes on board the ship, sub norm procedures harm the environment. With the majority of ship recycling capacity located in third-world countries, there are further challenges such as lack of legislation, lack of safety, lack of environmental awareness as well as a lack of emergency preparedness. Inevitably, lack of a global and local regulatory framework resulted in ships being dismantled in undesirable conditions adversely affecting the nature and human life. The impact of ship recycling has been severely criticized by governmental, international shipping authorities as well as non-governmental organisations. As a result of the everlasting negative images from ship recycling yards and the growing concern about the health and environmental impacts, international regulators were forced to focus on developing international regulations and standards. The International Maritime Organization’s (IMO) Hong Kong Convention (IMO, 2009b) and the European Union’s Ship Recycling Regulation (EC, 2016b) are examples of the aforementioned new regulations.

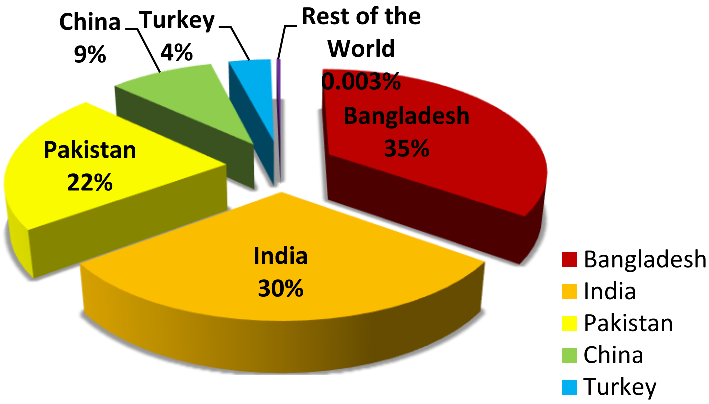


Figure 1.1: Main ship recycling destinations in 2016 in terms of LDT dismantled (NGO Ship Breaking Platform, 2017)

IMO has focused on the occupational and environmental problems of the ship recycling industry and adopted “The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships” which is also known as the “Hong Kong Convention” (IMO, 2009a). The convention aims to “ensure that ships, when being recycled after reaching the end of their operational lives, do not pose any unnecessary risk to human health and safety or the environment” (IMO, 2009). Convention adopted in 2009, and it would enter into the force 24 months after it is ratified by 15 states (representing 40% of world merchant shipping by gross tonnage) (IMO, 2009). Unfortunately, it has not been ratified yet by the required number of states and therefore has not yet entered into force to date.

Another regulation regarding ship recycling was adopted by the European Commission in 2013, “Ship Recycling Regulation” (EC, 2013). The primary objective of the Ship Recycling Regulation is minimising the adverse effects of recycling the EU-flagged ships (EC, 2016b). The regulation brings forward the requirements of the Hong Kong Convention and contributes to its global entry into force. EU’s ship recycling regulation includes additional safety and environmental requirements compared to the Hong Kong Convention. EU Ship Recycling Regulation will enter into force in 31st of December 2018 and requires all end-of-life ships with EU flags to be recycled in the facilities that are listed in the European list of approved ship recycling facilities.

Both regulations require ship recycling facilities to comply with the new standards, such as appropriate infrastructure, establishment of procedures and techniques to minimise, reduce, prevent the hazards and risks, systems to control any leakages. Therefore, both regulations require some changes and investments to be done in the ship recycling yards. Considering that the majority of the yards in South Asia does not meet the criteria, these regulations are especially critical for South Asian yards. Ship owners will have to recycle their ships in the "green" ship recycling yards due to the Hong Kong Convention and EU Ship Recycling Regulation which will force ship recycling yard owners to invest. In addition to investments, yards will also need to change the current operations to safer operating procedures which will also increase the costs of the yards (extra costs from the HSE measures and safe operating procedures). In order to compensate the investments and increased costs, ship recycling yards need to increase their revenue from the end of life ships or decrease the costs of the dismantling operations.

These regulations will also have an impact on the "green" ship recycling yards. Currently the cost of the "green" ship recycling yards are higher compared to subnorm yards in South Asia, China and Turkey due to the higher HSE related costs and worker costs. However, there is an opportunity for green yards as the costs of the yards in South Asia, China and Turkey will increase, it is easier to compete with these yards. If the costs of the yards can be reduced and the profit can be increased, green yards can compete with the subnorm yards. On the other hand European Community Shipowners' Associations states that total recycling capacity of the approved list is around 300,000 LDT which is not enough capacity to recycle all EU flagged ships (ECSA, 2018). Therefore, there is also a need to improve the capacity of these yards in order to meet the need of the industry.

Today, the ship recycling industry is currently going through a transitional phase where scientific support and technical approaches are needed more than ever before. One of the solutions to the capacity problem mentioned above is to increase the efficiency and productivity of the ship recycling facilities through optimisation of the ship recycling processes. Optimising the ship recycling processes will not only decrease the costs, but it will also increase the output of the yards, increase the earnings and in the long term it will increase the capacity of the yards. No study within the current body of literature focuses on increasing the productivity of the ship recycling facilities. Manufacturing, production, service and similar industries address their productivity problems through detailed simulation approach and to optimise the way they work. Therefore, a similar approach is needed for the ship recycling industry. Modelling and simulation studies in the literature (Creese et al., 2002, Ahluwalia and Govindarajulu, 2005, Adamides et al., 2006, Alkaner et al., 2006a, Pylarinou et al., 2008, Koumanakos et al., 2006, Pylarinou et al., 2006) for ship recycling focus on the simple calculation of costs and revenue but do not go into the detail of improving the situation or addressing any productivity problems. Similar studies exist in the literature for shipbuilding yards, port operations and maritime operations and are being utilised in the design and improvement of operations. However, this approach has not been applied to the ship recycling industry as it requires extensive data and investigation of different recycling processes.

This thesis addresses this gap through the development of a simulation method for ship recycling industry to design and optimise the ship recycling yards. The main aim of this study is to increase the productivity of ship recycling yards and optimise their procedures towards achieving cost-efficient and responsible facilities for the future. This aim will be achieved through the development of a framework to improve the efficiency of the ship recycling yards through implementing discrete event simulation methodologies. In order to achieve this aim, first, the current process models for different ship recycling methods in the five countries (Bangladesh, India, Pakistan, China and Turkey) were investigated, and the problems in the current process were identified. As a next step, simulation models in the ARENA discrete event simulation software with current and alternatives practices/processes for every step of ship recycling were prepared and presented.

This approach will also assist the industry to improve their operations. It will be possible to implement this framework for all different docking techniques;

different surface preparation technologies, cutting technologies, lifting technologies can be included in the models for the simulations. Also, this framework can also assist the ship recycling yards to make investments or help planning in long-term through different what-if analysis examples presented in this thesis.

1.3 Terminology

Ship recycling is also referred as ‘ship dismantling, scrapping, breaking, demolition or vessel breaking and dismantling. In order to have integrity through the thesis, ship recycling is selected as the single terminology.

Table 1.1: Stakeholders and terminology used (Modified from: Mikelis, 2012)

Terminology	Used By
Dismantling	NGOs, Basel Convention, Ministries of environment
Breaking	ILO, NGOs and Country delegates from India at IMO discussions (Usually used in relation to beaching)
Demolition, demo	Brokers
Disposal	Often used in shipping statistics
Scrapping	Ship owners and joint working group IMO/ILO/BC
Recycling	IMO, Ministries of transport, and ship owners with a defined end-of-life vessel policy

1.4 Approach Adopted

The critical review (Chapter 2) identifies the knowledge gap in the design and optimisation of the ship recycling yards to enhance the production capacity of the ship recycling yards. The aim of this research is to address this gap through discrete event simulation and creation of novel framework for developing and improving ship recycling yards. Previous simulation studies in ship recycling limited to studying specific theoretical concepts or high level material flows. Current research in literature does not support industry to address facility lay out and production improvements. Therefore, this PhD study adopts a simulation based approach to design and optimise the ship recycling yards. Aforementioned approach is demonstrated in the diagram shown in Figure 1.2.

Overall, this PhD study can be described in three main phases: Study and identification phase, Planning and Development phase, and Implementation and Analysis phase.

1.4.1 Study and Identification Phase

Before starting the development of framework, it was important to conduct a comprehensive investigation of the literature on the ship recycling industry. The outcomes of this investigation, which will be summarised in Chapter 2 and Appendix A of this thesis, demonstrated that studies focusing on the efficient design and optimisation of the ship recycling yards are very limited. Therefore, the research conducted in similar industries (ship building industry and other dismantling/recycling industries) needs to be investigated in order to comprehend the approach and implement it to ship recycling with all the important factors. In order to develop a valid approach, simulation methods will be studied in detail. Probability, random variables, probability distributions were investigated to identify the best approach to link the collected data to functions and to utilise them in the models. Moreover, simulation tools will be studied to find the suitable tool to develop simulation models for ship recycling.

Simulation studies for the development and optimisation of shipyards and ship building operations will be reviewed and the applicable approaches to ship recycling will be utilised in the framework development. Even though some aspects are similar between ship building and ship recycling industry, development of simulation model is different as one focuses on the assembly and the other focuses on the disassembly. In order to address this difference, simulation studies on the dismantling and recycling facilities will be also investigated to understand the approach on the dismantling modelling.

Moreover, in order to develop the design framework for the ship recycling yard, existing studies on the layout design will be investigated. Different approaches to the facility layout problem will be investigated and the advantages and shortcomings of these approaches will be considered. Then their potential for implementing them in the ship recycling will be investigated and developed method will be integrated into the framework developed in this study.

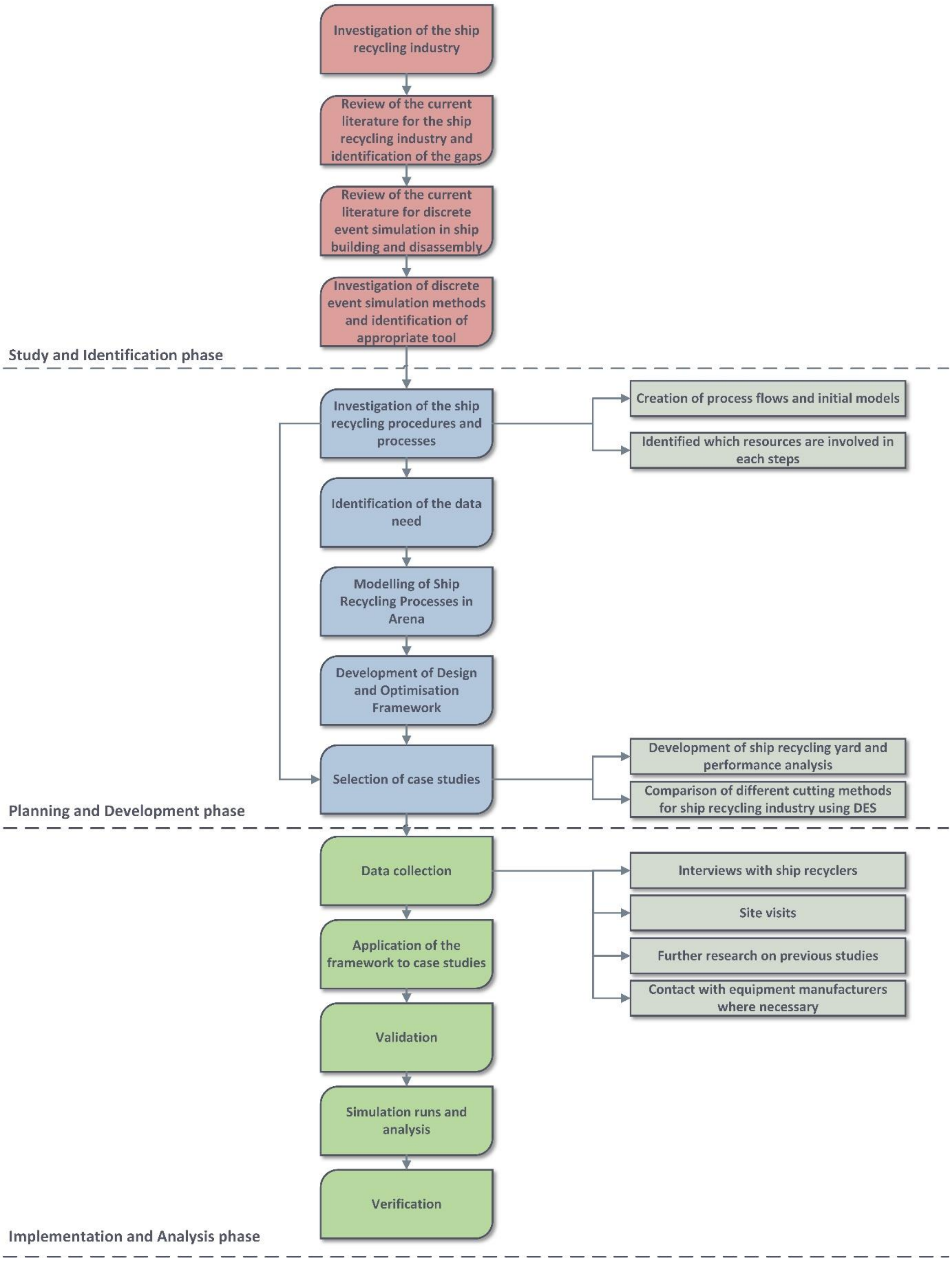


Figure 1.2: Approach adopted and phases of this thesis

1.4.2 Planning and Development Phase

Review of the literature in the previous phase demonstrated that;

- understanding of the ship recycling processes is essential to develop the ship recycling simulation models.
- Step-by-step ship recycling process flows needs to be generated as the literature is limited and focused on specific countries.
- different ship recycling processes should be compared and (if possible) a standard ship recycling process flow (that can be modified and applied on each docking method) should be generated
- Resources involved and data required on each step should be identified

In the literature, ship recycling process investigation studies exists but only a few of them creates the process in flowcharts, which is easy to understand and easy to transform to simulation model. Therefore, in this phase of the thesis, ship recycling processes in different countries will be investigated through the review of the literature, field trips (yard visits), and interviews with yard owners and other stakeholders to create the ship recycling process flows and collect data from ship recycling yards.

Ship recycling procedures will be divided into four different categories according to the docking type. Then ship recycling processes for each docking type were investigated along with the country that applies the method. Step by step process model flow diagrams will be created, and resources involved in each step and the data requirement of each step were will be identified (Appendix C) in order to facilitate easier model building and transformation to simulation tool. After creating the detailed process flows, different ship recycling approaches will be compared and a generalised ship recycling process flow which can be modified and applied to specific cases will be created.

Following the successful development of generalised ship recycling process, generated flow will be transformed to a simulation model. The logic of the develop model will be validated and verified with the help of ship recycling industry experts. These simulation models will be utilised in the design and optimisation framework that will be developed in this thesis.

Another finding of the literature review was the lack of the ship recycling yard design and optimisation framework for the enhanced productivity. Therefore, a novel ship recycling yard design approach will be developed to address the gap in the literature. The developed framework will be able to answer two different needs;

- The first use will be the ship recycling yard design framework, which utilises the facility layout development methods that was investigated during the literature review (and integrates the simulation models in the decision stage).
- The second use of framework will be the ship recycling yard process optimisation framework, which focuses on the improvement of the efficiency of the yard through the optimisation of different parameters (e.g. resources, technology).

1.4.3 Implementation and Analysis phase

Following the development of the simulation models and the framework, the capabilities of the developed approach will be demonstrated through a case study.

The simulation approach requires a comprehensive data on the operation, process times and costs to be successful. Therefore, a data collection campaign will be conducted to gather the missing data. A field study will be organised to collect operational data from a real ship recycling yard(s). The data collection study in the yard will be combined with interviews with recycling experts, other stakeholders, and equipment manufacturers where necessary.

Moreover, ShipDISMANTL and DIVEST projects also collected partial data on the operation and the appropriate data will be utilised within the case study (collected data is summarised in the Appendix D). A case study will be determined in advance to focus on data collection efforts. Once these phases are completed the developed framework will be tested and will be validated using the data collected. Furthermore, alternative ship recycling yards and processes will be modelled and compared using the simulation model to identify the most feasible designs and processes.

1.5 Structure of the Thesis

This section summarises the layout of this thesis. In this thesis, Chapter 1 is a general introduction to the research topic, and generic information about the ship recycling industry has been given along with the problems of the industry in the last decade. Also, the focus of this study has been summarized in this chapter. In Chapter 2, detailed information on ship recycling is given for the readers. A comprehensive literature review has been conducted and the gaps in the literature with regards to ship recycling are reported in this chapter. Also, existing studies on discrete event simulation for ship recycling, shipbuilding and maritime industry was also reviewed in in Chapter 2. The research question, aims and objectives are given in Chapter 3. In Chapter 4, ship recycling methods around the world were investigated in detail, generic process flows were created, and ship recycling simulation models are developed by using the ship recycling process flows created. Chapter 5 discusses the development of the ship recycling yard using the models and demonstrates a framework to design and optimise a ship recycling yard. The use of framework is demonstrated in Chapter 6 on a yard in EU to design and optimise the process as a case study. Chapter 7 uses of the framework and discrete event simulation and compares different recycling technologies available through a case study for secondary cutting zone optimisation. Chapter 8 discusses the recommendations and presents the conclusions.

1.6 Chapter Summary

This chapter has explained the background of the ship recycling industry, problems and summarised the approach of this study to tackle these problems.

Chapter 2 Literature Review

2.1 Chapter Overview

This chapter first summarises the current situation of the ship recycling market, factors affecting the decision to scrap a ship, ship recycler countries around the world with their current practice of ship recycling, and current laws and regulations in order to provide the reader with an insight on ship recycling. Next, the current literature of the ship recycling was investigated to find the gap in the extant body of the literature and the findings are reported along with the gaps identified in the literature. The gap area that this thesis aims to address is also discussed along with the studies in this area following the literature review.

2.2 Ship Recycling Industry

Ship recycling is a critical step in ship’s life cycle, which all valuable materials are recovered, reconditioned, reused or recycled. Ship recycling, similar to any other recycling industries, can be considered as the most environmentally friendly option for end-of-life ships compared to other options such as reefing or abandoning the vessel. The range of material, equipment and machinery that can be reappraised from end-of-life ships is extensive (Table 2.1) and have the potential to be reused, repaired, remanufactured and recycled. This is particularly important for developing countries as these materials can be reused in different industries; e.g. metal from the ship can be rerolled/melted and can be reused in the construction industry. Furthermore, other equipment on board ships can be utilised in ships (during refit or repair) or other industries (e.g. diesel generators are often used in factories). Therefore, the ship recycling industry benefits the economic development of the country it is located in.

Table 2.1: Summary of the equipment on board a ship (modified from (The SFI Group System, 2001, Bletsas et al., 2018))

Section of the ship	Valuable items
Hull of the ship	Hull structure and Superstructure (steel) Structural bulkheads, decks (steel) Door, hatches, and scuttles, seats, supports, and masts (steel) Control surfaces Structural castings, Forgings, Fastenings
Equipment for cargo	Cargo equipment and machinery including systems for vessel cargo, loading/discharging systems, Cargo winches and hatches Cargo Handling Equipment Lifts and Lifting Appliances Portable Lifting Equipment
Equipment	Ship-specific equipment, machinery, navigational equipment, manoeuvring machinery Anchoring equipment, communication equipment. Gyro`s, compass, antennas, displays, alarms, panels, con Radar Navigational Aids Propellers, Rudders, Stabilisers Anchor, Capstans Television, Radio & Satellite Communications
Equipment for accommodation and working environment	Equipment machinery and systems for lifesaving, accommodation, catering, sanitary systems. General Fittings Boats and Lifesaving Equipment Furnishing and Fittings Galley, Laundries & Workshop Equipment Accommodation & Medical Stores
Machinery Main Components	Primary components e.g main and auxiliary engines, propulsion plant, boilers and generators. Main Machinery Auxiliary Machinery Turbines Generators
Systems for Machinery Main Components	Systems serving main machinery components, e.g. fuel, lubrication, exhaust, automation systems Fuel Service Systems Air Supply & Exhaust Machinery Control Tanks
Common Systems	Ship systems, e.g. bilge and ballast, firefighting, and electrical distribution. Waste Disposal Electrical Power Distribution Equipment & Cabling Lighting Equipment Air Conditioning, Ventilation and Refrigeration Systems

Even though ship recycling is economically beneficial to whole industry: as it provides jobs for workers, raw materials for the construction sector, and economic incentives to recycle, it remains a contentious issue. Ship recycling is a very hazardous industry and therefore, the process of dismantling the ship is very complicated to manage. Also, the industry located in the third-world countries where occupational health and environmental protection are not addressed. Understanding the background of ship recycling is very important in order to assess the current status and state of the art as well as the future potential of this industry.

There has always been ship recycling, but as an industry ship recycling had not appeared until the industrial revolution and World War II (McKenna et al., 2012). In the past, ships were broken apart, and their wood (if the wood is high quality) were used in the new ships and other constructions (LR, 2011). For example, Great Marlborough Street Store of Liberty was constructed from the timbers of HMS Impregnable and HMS Hindustan (Liberty, 2011). After World War II, a large number of vessels were required to be dismantled, and approximately 500,000 tonnes of high-quality steel were scrapped from these vessels (LR, 2011). Until the late 1970's, ship recycling continued in the industrialised countries (such as Germany, Italy, United Kingdom, the United States and Scandinavian countries) often as a parallel activity to the ship repair and refit. However, the industry caused significant health, safety and environmental problems in these countries; some due to the nature of the work and some due to the significant amount of hazardous materials (Wu et al., 2015). As a result of these problems, public pressure forced regulators to act against the ship recycling practices within the industry in developed countries. Consequently, much more stringent regulations came into force in these countries which increased the cost of the ship recycling yards. In the meantime, the steel need of the industry in these European countries had also decreased. As a result of the steel demand and low cost, the ship recycling industry shifted to developing countries to the east, to Asian developing countries where there is a need for steel, equipment and other minerals. However, in these developing far-east countries, while the labour force is cheap, laws on human and environmental health are either loose or non-existent (Khan et al., 2012, YPSA, 2012a, Wu et al., 2014).

Today, ship recycling is mainly carried out in five major countries, Bangladesh, India, China, Pakistan, and Turkey as 99% of the ships, by volume, are recycled in these five countries (NGO Ship Breaking Platform, 2014, 2015, 2016, 2017).

2.2.1 Current Market

This section will present information about ship recycling industry in Bangladesh, India, China, Pakistan and Turkey. More detailed information on ship recycling process and facilities will be given in Chapter 4 of this thesis.

Bangladesh currently leads the ship recycling industry (in terms of gross tones dismantled) (Figure 2.1). Bangladesh is followed by India, which is followed by China, Pakistan and Turkey in terms of the steel dismantled.

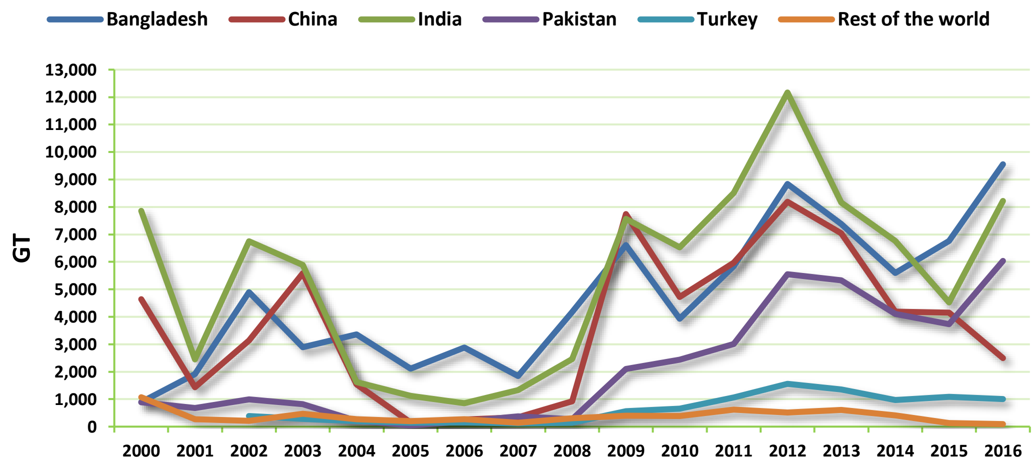


Figure 2.1: Ship recycling capacity according to countries (in '000 gross tonnes), compiled from NGO Ship Breaking Platform (2010, 2011, 2012a, 2013a, 2014a, 2015, 2016, 2017), Mikelis (2013a), Shipbuilders' Association of Japan (2016).

2.2.1.1 Bangladesh

The Ship recycling industry in Bangladesh was born when the Greek ship "MD Alpine ran aground on the shores of Bangladesh, Sitakunda and the ship remained in its place until 1964 because it could not be floated back. In 1964, the ship was bought by the Chittagong steel house and it was dismantled by the local workers (YPSA, 2012b) which started the industry in Bangladesh. Furthermore, in 1971, Pakistani Ship Al Abbas was damaged during the war, and it was later salvaged and then brought to the seashore where Karnafully Metal Works bought the ship as scrap. In the 1980s, the ship recycling industry started growing when the developed countries did not want to recycle ships because of the strict regulations and laws. Since 1980, the industry has managed an average of 14% growth each year (Ahammad and Sujauddin, 2017). Today the majority of the Bangladesh ship recycling industry is located in Sitakunda coast near Chittagong, occupying 12 km of the coast (Sujauddin et al., 2015b). An overview of the shore can be seen in Figure 2.2.

Figure 2.2: Chittagong Region Shore: Ship Recycling yards along the coastline (Google Maps, 2015b)

Currently, Bangladesh leads the industry in terms of the volume of the ship dismantled. Globally 700 ocean-going vessels are scrapped each year on average, and more than 100 of them are scrapped in Bangladesh (NGO Ship Breaking Platform, 2017). It is estimated that approximately 30 percent of the world's Light Displacement Tonnes (LDT) was scrapped in Bangladesh during the period 2000-2010. The ship recycling business slightly declined in 2009-2010 period due to the global recession and stricter enforcement of national laws on shipbreaking in Bangladesh. India became the leader in terms of volume dismantled until 2012, but this recession period did not last long and the industry kept growing after 2012. In 2015, Bangladesh dismantled the 33%

of the ships, India dismantled 22% and Pakistan dismantled the 18%. Bangladesh took the leadership back from India in terms of the volume dismantled annually around the world (NGO Ship Breaking Platform, 2017). There are several reasons behind this success, but the most critical factor is the geographical conditions of the Sitakunda beach, which has a long and uniform intertidal-subtidal zone with differences up to 6 meters. The weather conditions are stable, and the area is protected naturally by the Bay of Bengal (Hossain and Islam, 2006).

Ship recycling industry has significant economic benefits to the Bangladesh (Hossain and Islam, 2006, Mizanur Rahman and Mayer, 2015, Sujauddin et al., 2015a) Since Bangladesh is a developing country, the domestic demand for scrapped steel is very high. Between 50% and 60% of the recovered steel is used in rerolling mills in Bangladesh (Ahammad and Sujauddin, 2017). In addition to the steel, other types of metals (such as copper, aluminium) are also recovered from the ships and either used in domestically or exported. Apart from raw materials and metals, the ship dismantling industry also supports the community by providing job opportunities (directly in the yards or indirectly through the subsectors of the industry) (Jobaid et al., 2014, Hossain, 2015). The labour costs are very low and currently, approximately 40,000 workers are employed in the yards who are mostly migrant workers (ILPI, 2016).

However, Bangladesh recycling industry is criticised for putting the workers in hazardous working conditions, causing the environmental pollution and using the child labour in the yards (Hossain and Islam, 2006, FIDH et al., 2008, Alam and Faruque, 2014, Jobaid et al., 2014, Hossain, 2015, Zakaria et al., 2012). Several different NGO's reported (Kumar, 2009, NGO Shipbreaking Platform, 2009, World Bank, 2010) on the overall condition of the ship recycling industry in Bangladesh. Moreover, combined with the accidents and public (national and international) reaction these reports created a big impact when they were published. This put the ship recycling industry under the spotlight once more. Since then, Bangladesh government started to put a lot of effort to fix the industry's problems and the situation is much better today. Despite the improvements, there is still room for major improvements for the Bangladesh ship recycling industry (ILPI, 2016). The industry is still substandard considering the dangerous activities, lack of hazard awareness and lack of training of the workers. Accidents are still prevalent but the documentation and reporting of these accidents are not very good. From 2011 to 2015, 53 workers lost their lives while 78 was injured (Dey, 2016). However, since the record keeping is not conducted correctly, there is no way of knowing the accuracy of these numbers.

Apart from the occupational health and safety problems, there are also environmental problems caused by the industry. The waste management in the industry is abysmal. Most of the toxic materials from the ships contaminate the soil, air and water as the mitigation measures are non-existent. Nøst et al. (2015) report that the air samples collected from the city of Chittagong had a very high concentration of PCB’s, PAHs, HCB, DDTs and SCCPs. According to the Sarraf et al. (2010), a large amount of toxic wastes will accumulate in Bangladesh from 2010 to 2030. Authors of the report estimate 79,000 tons of asbestos, 24,000 tons PCB, 210,000 tons ODS, 68,200 tons of paints and other wastes to be accumulated around the yards.

Currently, with the support of the international bodies such as IMO and NORAD, Bangladesh ship recycling industry is going through a transitional process. Ship recycling yard owners have been investing in the yards to improve the conditions and to comply with the regulation changes.

2.2.1.2 India

Ship recycling activities in India started in the sixties with the small barges and coastal wrecks and remained as a causal industry until 1979 when the Government recognised the industry as a “small-scale industry” (DIVEST, 2009a). Ship recycling industry in India started in 1983 with the recycling of the ship namely, “Kota Tenjong” (Demaria, 2010). India was the leader in the volume dismantled until 2014 but now currently ranked second amongst the ship recycling in the 2015 and 2016, according to NGO Ship Breaking

Platform's Annual Report (NGO Ship Breaking Platform, 2016, NGO Ship Breaking Platform, 2017). 194 ships were recycled in 2015 with a total of 4.5 million GT of recycled ships, and 305 ships were recycled in 2016 with a total 8.2 million GT of recycled ship (NGO Ship Breaking Platform, 2016, NGO Ship Breaking Platform, 2017).

There are several ship recycling regions along the coast, but The primary ship recycling locations in India are Alang and Sosiya villages of Gujarat state (the coastline of Alang can be seen in Figure 2.3) which is located on the bank of the Arabian Ocean (YPSA, 2012c). The tidal characteristics of these two locations provides the opportunity to beach and dismantle the ships on the shore (DIVEST, 2009a). Nearly 160 ship recycling yards occupies the 12 km beach of Alang (Reddy et al., 2003b, Asolekar, 2006, Demaria, 2010, Hiremath et al., 2015).

Figure 2.3: India- Alang Region Shore: Ship Recycling yards along the coastline (Google Maps, 2015c)

In the last five years, approximately 330 ships yearly in average are broken in Indian ship recycling yards. In the last decade, India was the market leader on the total tonnage of dismantled ships, however Bangladesh ship recycling industry took over the leadership in the last two years (NGO Ship Breaking Platform, 2013, 2014, 2015, 2016, 2017). Currently in India out of 170 SRFs (approx.) 35 are active at the moment (SENSREC, 2015). According to ILPI, 35,000 permanent and temporary workers are being employed directly in the

Indian ship recycling industry (ILPI, 2016). Majority of these workers are migrant workers from all over India.

After the Hong Kong Convention, India has improved the conditions in the ship recycling yards. However, the beaching method, which is still not recognised by the current conventions, is causing environmental damage to the ship recycling areas.

2.2.1.3 China

China is currently is the third country in the total capacity of ship recycling annually. The official start of ship recycling industry in China dates back to 1960s (Du et al., 2017) and the current ship recycling capacity in China is about 3,000,000 LDT/year in the approximate 80 yards in the Jiangsu Province and Guangdong provinces (Jones, 2007). China was once the world leader in ship recycling (by 1993 nearly half of the ships were scrapped in China (Puthucherril, 2010a) but similar to other ship recycling nations, the industry faced some fluctuations depending on the overall market (Du et al., 2017). For example, Chinese ship recycling market almost stopped in the 1980s due to the increased tax on imported tonnage, on the other hand by mid-1990s (China was the leader of the market in 1993) half of the end of life ships were sent to China for recycling (Galley, 2014). Again in 2006, industry only demolished 170,000 LDT due to the increasing scrap price but in 2009 industry reached its peak in 2009 (Du et al., 2017). According to China National Ship Recycling Association, a total of 44 million DWT ships were recycled, 11 million tons of ore were salvaged, and (combined with the reduced mining activity) CO2 emissions were reduced by 11.5 million tonnes between 2011 to 2015 (Zhao, 2015, Du et al., 2017).

The ship recycling process in China is different from the practice in Indian subcontinent and it is based on dry-docking and quayside systems. In the quayside method, ships are dismantled in a reverse way of the building process., rather than cutting chunks or slices as in the beaching method (Jones, 2007).

The HSE practices in the Chinese ship recycling yards are also better compared to India and Bangladesh, in 2005; The Chinese National Shipbreaking Association initiated a campaign to upgrade the HSE conditions in the yards, in a program partly supported by the China and the Netherlands (2005). Yards now provide better Personal Protection Equipment (PPE), HSE controls, lesser number of accidents compared to the yards in South East Asia (Du et al., 2017). On the other hand, costs associated with the safe and green yards mean that these yards can offer lower price to ship owners compared to Bangladeshi and Indian yards but, some ship owners prefer Chinese yards due to their better facilities and large capacities (Puthucherril, 2010a).

Even though Chinese ship recycling industry is a reputable, competitive and experienced, industry is facing problems such as supervision absence, excessive taxes, scrap ships' trading irregularities, awareness of environmental safety and so forth. (Du, 2012).

Nowadays, Chinese ship recycling industry is heading to unclear future. Chinese government recently issued a ban on the import of waste materials, including ships and offshore assets. This decision will affect the future of the ship recycling industry considering that China dismantled the 11 percent last year (NGO Ship Breaking Platform, 2017). The lost capacity needs to be replaced as soon as possible in order to sustain the industry.

2.2.1.4 Pakistan

Ship recycling industry began in 1947 (Kumar, 2009), the industry reached its peak in the 1970s and 1980s when 30000 workers were directly employed in the ship recycling yards (NGO Ship Breaking Platform, 2013b, Kumar, 2009, Sarraf et al., 2010). However,after 1980's Pakistan ship recycling could not compete with India and Bangladesh ship recycling yards due to the increased tax from the Pakistan government and the competition from the other countries with newer facilities, Bangladesh, India and China and currently, the industry is ranked fourth in the world and third amongst the South Asian ship recycling countries (NGO Ship Breaking Platform, 2016).

Currently around 6000 workers are employed in the approximately 34 yards scrapping around 1million tons of steel scrap (NGO Ship Breaking Platform, 2014b).. This is due to the intense competition from India, Bangladesh and China as well as the changes in the taxes and laws regarding ship recycling (Sarraf et al., 2010).

Today the Pakistan ship recycling industry is located in Gaddani where a 10-mile beach is located (Figure 2.4). Around 15,000 workers are estimated to be directly employed in the 68 operational yards (NGO Ship Breaking Platform, 2013b). In 2015, 81 ships were broken on the shores of Pakistan, in total sums up to 3.7 million GT (NGO Ship Breaking Platform, 2016).

Figure 2.4: Gadani Region Shore: Ship Recycling yards along the coastline (Google Maps, 2015d)

On the occupational health and safety side, the number of accidents and the casualties are not very clear, as there is no reliable record keeping. Even though the accidents are not reported well, they are familiar similar to India and Bangladesh. For example, in 2012, 3 workers died when heavy iron rubble fell on them from the ship's deck (recyclingships.blogspot.co.uk, 2017, Farooq, 2012), 17 workers died and 58 were injured in the tragic accident in 2016 (Syed Ali Shah and Sasoli, 2016), 5 workers died from the fire in 2017 (Messenger, 2017).

Pollution and the dangerous operations are key concern for the Pakistani ship recycling industry (NGO Ship Breaking Platform, 2012b, 2013b, 2014b, ILPI, 2016). Accidents are very common, in 2016, as a result of an explosion during the dismantling of a tanker more than 30 worker lost their lives and more than 50 workers were injured. Even though the death tolls are very high, there is no evidence that ship recycling yard owners take the necessary measures to prevent accidents and casualties (e.g. workers are not provided with the PPE, are forced to work overtime with no work or vacations) (ILPI, 2016, NGO Ship Breaking Platform, 2013b). Also, there is no infrastructure in order to treat the hazardous waste in ship recycling yards which is a big concern for the human and environmental health (NGO Ship Breaking Platform, 2012b, NGO Ship Breaking Platform, 2013b, NGO Ship Breaking Platform, 2014b) (ILPI, 2016). Currently, Pakistan government pressuring the ship recycling yards to improve the conditions of the ship recycling yards. Time will show if the efforts of the government will suffice or not.

2.2.1.5 Turkey

Turkey is the only OECD country amongst the top five ship recycling countries (fifth country as per the volume scrapped). Ship recycling activities in Turkey started in the mid-seventies. However, industry developed after 1984 when the Turkish government allowed importing scrap ships (Vardar, 2004). In 2012, the industry reached its peak and dismantled almost 1,600,000 tonnes of steel (927,000 LDT). Currently The annual recycling capacity of the Turkish ship recycling industry was being estimated as 1,000,000 LDT/year in total of the 22 shipyards along the coast of the Aliaga region of Izmir, Turkey (DTO, 2016) and 1200 people in total are employed in the yards (GEMISANDER, 2018). The ship recycling site (Figure 2.5) is approximately 1,300m and occupies around 600,000 m^2 (Taylan, 2014).

Figure 2.5: Aliaga Region Shore: Ship Recycling yards along the coastline (Google Maps, 2015a)

In 2017, the European Union added 18 facilities in the European list of ship recycling facilities. All of these 18 facilities which are in total 1.1 million LDT are from EU member states. At the moment, none of the Turkish facilities made the list but seven facilities applied and were audited by the experts. Other yards are currently completing the compliance procedure.

The condition of the yards has improved since the Turkish ship recycling yards were put in crosshairs when the GREENPEACE had published the report on Turkish ship recycling industry, which was criticising the Turkish ship recycling industry, especially the hazardous waste management in the Aliaga region (GREENPEACE, 2002). This report has led to improvements in the long term with the actions taken by both government and yards themselves. Better hazardous waste management facilities were built and serve the Turkish ship recycling industry since then. Compared to the top three countries, Turkey has good waste removal and management system (NGO Ship Breaking Platform, 2009). Current Turkish environmental laws and regulations that are related to shipping recycling entirely implements the guidelines of the Basel Convention. For the handling of hazardous materials, a Waste Management Center as part of the Shipbreakers Association of Turkey has been created, and the experts of this centre handle the initial handling and removal of hazardous materials. These teams are trained and certified by Ministry of Environment of Turkey, and they are capable of handling a wide range of materials from asbestos to radioactive materials (DIVEST, 2009a).

2.2.2 Ship Recycling Methods According to the Docking Type

Ship recycling yards in the above countries and the rest of the world follow different types of ship recycling methods in their operation. The methods to recycle the ship are mainly similar: cutting parts from the ship and dismantling further to the requirements. The main difference is the docking type that is used during the operation which mainly depends on the location of the yard.

2.2.2.1 Beaching

Beaching is the term used for dismantling ships at the intertidal zone of a beach (Jain, 2017). Beaching is the most common method in South Asia; around two third of the world's end-of-life ship capacity is dismantled on a beach, making it the dominant current practice in ship recycling (Hougee, 2013, LITEHAUZ, 2013, LR, 2011). It is practised in Bangladesh, India and Pakistan, who provide 69% of the world's recycling capacity in GT terms (Leyers, 2014). According to NGO's reports, 469 ships were beached (73% of total number) in 2015, 641 ships were beached (62.5% of total) in 2014, 645 ships (71% of the total) were beached in 2013, 922 ships were beached (68% of total) in 2012 (NGO Ship Breaking Platform, 2014b, NGO Ship Breaking Platform, 2013a, NGO Ship Breaking Platform, 2015, NGO Ship Breaking Platform, 2016). Although there is a decrease in the number of the ships that were beached compared to previous years, the percentage remains the same.

The main reason behind the common usage of the beaching method is that the costs related to this method are much lower (Sarraf et al., 2010) and the need of infrastructure is very low. This method is suitable in the regions with the high difference of tide levels. In the beaching method, the ship is steered to the shore on the high tide using the ship's own power. Once landed on the beach, ships are then pulled higher up the beach using the winches and chains (LR, 2011). Workers then start the dismantling and cutting the hull. In this method, big blocks are cut from the ship; they are dropped on the beach using the gravity method. Cut blocks are then cut into smaller pieces for transport on the beach or transferred to secondary dismantling zone for cutting into smaller pieces. As blocks are cut, ship becomes lighter hence easier to pull up the shore using winches and chains. This procedure is repeated until the dismantling operation is finalized.

While the beaching method is the most common method, it is also considered as the riskiest method for the environment and occupational health and safety. Due to the practices in the countries where the beaching method is applied, the ship recycling industry has a negative image. During the dismantling operations, the contaminants and hazardous materials on board the ship are spilt on the ground and then to the sea/ocean via the tide. Unfortunately, workers also are exposed to these hazardous contaminants during their daily tasks.

Beaching method is the most criticised method as most the contaminants in the ship and it is actually was the major driver for the development of Hong Kong Convention (NGO Shipbreaking Platform, 2009, LITEHAUZ, 2013). Especially the liquids and hydrocarbons directly released to the beach and to the sea due to the tide conditions. Unfortunately, the ground and the sea around the ship recycling yards which are using this method are highly polluted due to these facts.

2.2.2.2 Slipway

Slipway method, which is also known as the landing or non-tidal beaching method, has some similarities with the beaching method (LR, 2011). The main difference of the slipway method is that the infrastructure or constructed pier on the landing zone (The ground is commonly concrete and there are more measures to prevent pollution compared to beaching method) and the tide. In the slipway or landing method, the ship is docked to the shipyard's slipway area which mostly starts lower than the sea and has a low inclining angle. This method is mainly used in Turkey and some ship recycling yards in the EU where there is no tidal difference or very minimal.

2.2.2.3 Quayside

The Quayside (or also referred as Alongside) method is mainly used in China, US and Belgium (Hougee, 2013). In this method, the ship is berthed on the pier and shipyard and the process starts from the top and the approach is top to bottom in the vertical direction (LR, 2011, Sivaprasad, 2010). The parts of the ship are cut and removed until reaching the double bottom while the de-ballasting processes conducted carefully to prevent any leakage to the sea. Depending on the yard's capacities, the remaining double bottom, "canoe", either lifted to the land for the further cutting or transferred to the dry dock (LR, 2011).

2.2.2.4 Dry-Dock

In this method, end of life ship is taken in a dry-dock of the yard. This method is often considered safer and cleaner cleanest ship recycling method compared to other alternatives. The risk of polluting the environment stays at a low level due to the fact that all the contaminants in the ship stay in the dry-dock. Once the recycling operation is completed, the dock is cleaned and flooded for the next end of life vessel (LR, 2011).

2.2.3 Challenges and issues in the ship recycling industry

In this section, the challenges in the ship recycling industry are discussed in order to diagnose the core issues. These issues are also important to identify the direction of this research. During the identification of the challenges and issues in the ship recycling industry, more than 200 publications were scanned using the keywords "ship dismantling", "ship recycling", "ship scrapping" in EThOS, ProQuest, Science Direct, and Scopus databases. Relevant publications from the scanned literature was categorised into seven main categories using the keywords and their area of interest: “generic review of the industry”, “law and policy”, “economic impact and analysis”, “health, safety and environment” “process analysis/best practice for safety”, “design for recycle and other engineering solutions”, and “process optimization and yard design”. The list of the studies that were reviewed and their categories can be found in Appendix A of this thesis.

One main challenge of the industry is the HSE hazards associated with ship recycling process. Ship recycling industry is one of the most dangerous industries in the world due to the hazards associated with the ship recycling industry. Studies show that the working conditions of yards are very dangerous (GREENPEACE, 1999b) and workers are constantly exposed to various hazardous materials that are extremely harmful to human health (Hossain et al., 2008, Salim, 2009, Hossain et al., 2016) (Chang et al., 2010). Health problems caused by the industry still arise even after 20 years (Logan and Lord, 2013). For example, asbestos is one of the common toxic wastes that can be found on the ships (GREENPEACE, 1999a, 1999b) and studies on ship recycling workers showed the elevated trend of asbestos exposure with cancer incidence for overall cancer, oesophagus cancer, and trachea, bronchus, and lung cancer among (Courtice et al., 2011, Wu et al., 2014, Wu et al., 2015). Apart from the asbestos, heavy metals exposure in the yards is also another concern (Mattorano et al., 2001, Deshpande et al., 2012). Moreover, recent research studies shows that exposure to emission is (inhalation, noise or even electromagnetic field) is an important hazard for ship recycling workers (Melton, 2008, DIVEST, 2012, Kurt et al., 2017). Apart from the health and safety of the workers, basic rights of the workers are not met and the living conditions in the yards are well below the standards (FIDH, 2002, Mashreque, 2005, Karim, 2009).

Unfortunately, accidents are also very common and the causes of the accidents has a wide range (impact with object, explosion, fires, suffocation, cuts, falls, slips, trips) (GREENPEACE, 1999b, Hossain et al., 2008, Neşer et al., 2008, Salim, 2009, Muhibbullah, 2013, Frey, 2015, Haque, 2016). In similar industries, all these hazards and risks can be reduced to the acceptable level manageable with proper mitigation methods (e.g. risk management and PPE), however, the hazard awareness and the knowledge of risk mitigation concepts are lacking in the ship recycling industry. Using appropriate risk awareness and assessment methods, accidents, injuries and deaths in the industry can be avoided (Kinigalakis and Karling, 2006, Rousmaniere and Raj, 2007, Andersen, 2008, Kinigalakis and Lindvall, 2008, Deshpande et al., 2013a, Hiremath et al., 2013a, Tunarli and Fet, 2013, Garmer et al., 2015, Kurt et al., 2015) but there are barriers that prevents the application. One of the barriers in applying the mitigation methodologies is the lack of accurate data on the accidents. Accident data, such as statistics, causes of the accidents or the consequences of these accidents, are not kept up to date, however, these statistics and reports can be very useful in the future to the yard and the industry as well (Kurt et al., 2013). The other obstacle on the application of these methods is the lack of awareness and understanding in the industry. This awareness and understanding of employees, employers and other stakeholders (such as policy makers and government officers) can be enhanced in ship recycling through structured education and training programmes (Shameem, 2012, Arslan et al., 2013a, Arslan et al., 2013b, Kurt et al., 2013, ShipDIGEST, 2013). Involvement of all stakeholders are particularly important as the capacity for monitoring and strong enforcement from the policy makers are needed to improve the conditions (Rahman and Mayer, 2016). For example, Indian Government has initiated many projects to defend human and environmental health which decrease of fatal accidents from 2.0 per 1000 workers to 0.13 per 1000 workers i.e. 93.5% decrease in the fatal accidents in the ship recycling yards from 2003 to 2011 (Hiremath et al., 2014).

In addition to worker health, environmental safety is another concern for the ship recycling industry. Ships contain a wide range of hazardous materials on-board the ships. Detailed analysis on sediments and soil samples around the yards show that ship recycling industry caused serious harm to the environment throughout the years (GREENPEACE, 1999a, 1999b, 2001a, 2001b, 2002). One of the most common contaminant is the heavy metals (e.g.

Fe, Mn, Cr, Pb, Hg, Cu, and Cd) which was found to be at the alarming stage around the ship recycling yards (water and soil) (Islam and Hossain, 1986, Tewari et al., 2001, Khan and Khan, 2003, Reddy et al., 2004a, Reddy et al., 2005b, Basha et al., 2007, Neşer et al., 2012b, Pasha et al., 2012b, Siddiquee et al., 2012, Hasan et al., 2013, Neser et al., 2013, Aktaruzzaman et al., 2014, Kara et al., 2015). In addition to the heavy metals, hydrocarbon contamination on the shores of recycling yards found to be over the permissible limits (Zhijie, 1988, Tewari et al., 2001, Reddy et al., 2005b, Dhar et al., 2012, Neşer et al., 2012a, Neşer et al., 2012b, Hossain et al., 2016). Moreover, paint chips from the ships also contaminates the soil and sea during docking and cutting operations) (Mahindrakar and Asolekar, 2006, Mahindrakar et al., 2008), and plastics from the ships are other source of pollution (Reddy et al., 2006). Emissions from the yards are another disturbing fact of the ship recycling (Tilwankar et al., 2008a) as studies showed the concentration of organic contaminants (PAHs, PCBs, DDTs, HCB, and SCCPs) in the air around the yards were very high (Nøst et al., 2015). Furthermore, the radiation accumulation around the yards is also worrying (Hossain et al., 2010). The primary reason for the environmental damage and the workers' exposure to the hazardous materials is the poor waste management in the ship recycling industry (Vuori, 2013). There is no established waste management infrastructure and majority of the hazardous wastes are dumped to landfills without any precautions or knowledge. There are several studies in the literature to record (and to estimate) the amount waste (Asolekar, 2006, Neser and Unsalan, 2008, Hiremath et al., 2015), to improve the waste management (Chaturvedi and Asolekar, 2006, Neser and Unsalan, 2008, Hiremath et al., 2015) and to reuse the generated wastes (Reddy et al., 2003a, 2004b, 2005a, Jain, 2017).

All these wastes and agents (i.e. heavy metals, hydrocarbons, paint chips, emissions and other contaminants) also effected the ecology, coastal and marine life around the ship recycling yards adversely (Amin and Billah, 2007, Abdullah et al., 2010, Demaria, 2010, Hossain and Rahman, 2010, Abdullah et al., 2013, Kutub et al., 2017, Hiremath et al., 2014). Traces of contaminants are found in the fish and other marine species (Hossain and Rahman, 2010, DIVEST, 2012, Hossain et al., 2016, Kutub et al., 2017) and bacteria levels in the surrounding seas found to be 17% - 605% more than control region (Tewari et al., 2001).

These negative images and the evident adverse effects of the industry forced policymakers to take an action in order to mitigate/minimize the impacts of the industry on human and environmental health. In order to solve the issues, three conventions were developed to regulate the activity of the ship recycling facilities.

- Basel Convention (The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel Convention, 1989)),
- The Hong Kong convention (The Hong Kong Convention for the Safe and Environmentally Sound Recycling of Ships (IMO, 2009a)), and
- The EU Ship Recycling Regulation (EC, 2013).

Details of these regulations are discussed in the following sections.

2.2.3.1 Basel Convention

The Basel Convention on the Control of Transboundary Movement of Hazardous Waste and Their Disposal, or also known as Basel Convention shortly, was adopted in 1989 and it came into force in 1992. Currently, 186 countries are parties the convention and 184 ratified the Convention (Haiti and United States signed but not yet ratified the Convention) (Basel Convention, 2018). The main objective of the Basel convention was to control the movement of the hazardous waste (from developed countries to developing countries) (Basel Convention, 2011). In addition to the Basel Convention, Basel Ban was also adopted in 1995, which is an amendment to the Convention. Basel Ban establishes a ban on export of hazardous waste from OECD and EU countries to non-OECD countries (EC, 2008). The entry into force requires ratification by three-quarter of the parties, and currently this number has not been reached yet (Basel Convention, n.d.).

The Basel Ban was integrated into EU Waste Shipment Regulation, therefore, it is legally binding to all EU Member States (DIVEST, 2009b). Even though end-of-life ships may become waste and be within the scope of the Convention, the enforcement is very difficult as it can also be defined as a ship under other international rules (COM, 2008, Argüello Moncayo, 2016). Therefore, implementation of the Basel Convention is not effective in practice (Watkinson, 2006, Moen, 2008, Sonak et al., 2008). The export ban under the EU Waste shipment regulation is hard to apply if a ship left OECD waters and the owner then decides to send it for recycling in non-OECD countries using more “convenient” flag states (Alcaidea et al., 2016). In order to implement the Basel Convention to ship recycling industry, additional precautions are needed (Watkinson, 2006). This challenge has led to the development of IMO Hong Kong Convention which was developed in order to address the gap in the Basel Convention (Regardless of the difficulties, currently the Convention continues to be applied as there is no international framework on ship recycling in force (SHIP_REC, 2014)).

2.2.3.2 Hong Kong Convention

The ship recycling was first brought to the attention of IMO (Marine Environment Protection Committee, MEPC) in 1998 and the committee agreed that the IMO should take more active role in ship recycling (Dimakopoulos, 2005). In 2002 MEPC decided to develop a guideline for ship recycling which was finalised the guidelines on December 2003 and, in December 2005 it was decided to develop a “new legally binding instrument on ship recycling” to facilitate safe and environmentally sound ship recycling (Mikelis, 2009).

The Hong Kong International Convention (HKC) for the safe and environmentally sound recycling of ships, (also known as Hong Kong Convention) was adopted in May 2009. Convention will enter in the force 24 months after its ratification by 15 States, representing 40 percent of world merchant shipping by gross tonnage and by states whose ship recycling capacity is not less than 3 percent of world's maximum annual ship recycling volume (IMO, 2009a). Only Norway, Congo, France, Belgium, Panama, Turkey and Denmark signed the HKC so far.

HKC aims to ensure that the end of life ships do not pose any unnecessary risk to human health and safety or to the environment (IMO, 2009b). The regulations in HKC cover the complete life cycle of the ship (the design, construction, operation and preparation of ships to facilitate safe and environmentally sound recycling) and the operation of ship recycling facilities in a safe and environmentally sound manner.

The HKC introduces the "Inventory of Hazardous Materials" which will be mandatory for ships to carry once the convention enters in the force (LR, 2014). Ships to be sent for recycling will be required to carry an inventory of hazardous materials. Once the convention goes into force, ships will go through an initial survey to verify that the hazardous materials on board the ship documented and the survey will be renewed until the final survey before the ship is sent for recycling. After this survey, the ship will be given IHM document which will be specific to each ship. Appendix 1 and 2 of the convention provide detailed information on the hazardous materials that must not be installed or used during the construction or repair of the ship.

Ships will need to be recycled only in the authorised ship recycling facilities. In order to be authorised, ship recycling yards will be required to provide a Ship Recycling Facility Plan which covers environmental protection, safety and training, emergency preparedness and response and systems for monitoring, recordkeeping, and reporting of discharges, emissions, and incidents (Hougee, 2013). Moreover, ship recycling plan that is specific to each ship that describes how the ship will be dismantled and how the hazardous material on board will be treated needs to be prepared. IMO published a guideline for the ship recycling facilities that covers the facilities, infrastructure, waste management and operation (IMO, 2012).

Compared to Basel Convention, it presents clear improvements of the present situation (Bhattacharjee, 2009), however, the enforcement of the Convention to end of life ships is not clear (Sundelin, 2008) (Jain et al., 2013). The convention has not come into force because not enough countries ratifies it. The structure of the convention (limited cover of the ships, does not include the further processing of hazardous materials, and being dependent on the signature of Bangladesh, China, India, Pakistan) may affect the acceptance and the success of the convention (Chang et al., 2010, Jain et al., 2013, Cameron-Dow, 2013). Moreover, the draft Convention does not fully succeed to allocate the costs caused by shipbreaking in a manner that is in accordance with principles of international environmental law (Yujuico, 2014).

2.2.3.3 European Ship Recycling Regulation

The European Parliament and the Council of the European Union adopted the Ship Recycling Regulation on 2013 and the main aim of the Ship Recycling Regulation is to reduce the negative effects of the ships flying the flag of EU Member States (EC, 2016b). Regulation brings forward the requirements of HKC; therefore, the other aim of the Regulation is to accelerate the ratification process of the HKC (Argüello Moncayo, 2016). Regulation has entered into force on 30th December 2013 and the latest implementation is 31st December 2018 (EC, 2013, Mikelis, 2013b, Jain, 2017). Regulation is applied to the ships flying an EU member flag and other ships that call at EU ports or anchorages (Alcaide et al., 2017).

Regulation introduced the “European List of Ship Recyclers” that EU-flagged ships have to be recycled in these listed “approved” ship recycling yards. (EC, 2016c). In 2016, December, European Commission has adopted the first version of the European list of ship recycling facilities (EC, 2016d). In this first list, 18 ship recycling yards were included in the list which was all from Europe. The detailed list of these yards is given in Table 2.2;

Table 2.2: European List of ship recycling facilities(Modified from European Commission (2016))

Name of the Facility	Country	Method of Recycling	The maximum size of the ship that can be recycled	Maximum annual recycling
NV Galloo Recycling, Ghent	Belgium	Alongside (wet berth), slope	L: 265 m, W: 36 m D: 12,5 m	34,000 LDT
Fornæs ApS	Denmark	Dismantling by quay and subsequent scrapping on impermeable floors with effective drainage systems	L: 150 m, W: 25 m, D: 6 m GT: 10,000	30,000 LDT
Smedegaarden A/S	Denmark	Dismantling by quay and subsequent scrapping on impermeable floors with an effective drainage system	L: 170 m, W: 40 m, D: 7,5 m	20,000 LDT
GARDET & DE BEZENAC Recycling	France	Floating and slipway	L: 150 m, W: 18 m, LDT: 7,000	16,000 LDT
Grand Port Maritime de Bordeaux	France	Alongside, drydock	L: 240 m, W: 37 m, D: 17 m	18,000 LDT
Les Recycleurs Bretons	France	Alongside, drydock	L: 225 m, W: 34 m, D: 27 m	5,500 LDT
A/S „Tosmares kuģubūvētava”	Latvia	Ship dismantling (wet berth and dry dock)	L: 165 m, W:22 m, D: 7 m, DWT:14,000, GT:200 - 12 000, Wt: 100 – 5,000 t LDT: 100 – 5,000	0
UAB APK	Lithuania	Alongside (wet berth)	L: 130 m, W: 35 m, D: 10 m, GT: 3,500	1,500 LDT
UAB Armar	Lithuania	Alongside (wet berth)	L: 80 m, W: 16 m, D: 6 m, GT: 1,500	3,910 LDT
UAB Vakaru refonda	Lithuania	Alongside (wet berth)	L: 230 m, W: 55 m, D: 14 m, GT: 70,000	20,140 LDT
Keppel - Verolme	The Netherlands	Ship Breaking	L: 405 m, W: 90 m, D: 11,6 m	52,000 LDT
Scheepsrecycling Nederland B.V.	The Netherlands	Ship Breaking	L: 200 m, W: 33 m, D: 6 m, H: 45 m	9,300 LDT
ALMEX Sp. Z o.o.	Poland	Piers and recycling plots on land-sea interface	L: 120 m, W: 20 m, D: 6 m, DWT: 6000, GT: 2,500, LDT: 2,500	4,000 LDT
Navalria - Docas, Construções e Reparações Navais	Portugal	Drydock dismantling, decontamination and dismantling on a horizontal plane and inclined plane, according to the ship's size	Nominal capacity of the horizontal plane: 700 tonnes The nominal capacity of the inclined plane: 900 tonnes	1,900 LDT
DDR VESSELS XXI, S.L.	Spain	Dismantling Ramp	Length: 84.95 meters (Ships up to 169.9 meters which can operate a zero rollover or negative ramp movement may be accepted depending on the outcome of a detailed feasibility study	0

Name of the Facility	Country	Method of Recycling	The maximum size of the ship that can be recycled	Maximum annual recycling
Able UK Limited	United Kingdom	Ship dismantling and associated treatment authorized with dry dock and a wet berth	L: 337.5 m, B: 120 m, D: 6.65 m	66,340 LDT
Harland and Wolff Heavy Industries Limited	United Kingdom	Ship dismantling and associated treatment authorized with dry dock and a wet berth	The main dock (the largest) is 556m x 93m x 1.2m DWT and can take vessels up to this size. This largest dry dock is 1.2 million DWT	13,200 LDT
Swansea Drydock Ltd	United Kingdom	Ship dismantling and associated treatment authorized with dry dock and a wet berth	L: 200 m, B: 27 m, T: 7 m	7,275 LDT

In addition to the requirements of HKC, a ship recycling facility shall operate from built structures, should prevent adverse effects on HSE including any leakages (in particular in sea-shore interaction) and should be able to safely manage and store hazardous wastes in order to be included in the European List (EC, 2013). Even though the regulation takes the HKC as a base, the regulation also includes additional safety and environmental requirements. Perfluorooctane sulfonic acid (PFOS) was added to Appendix 1 and Brominated Flame Retardant (HBCDD) was added to Appendix 2 of the hazardous materials list that HKC introduced (EC, 2013).

All these three regulations will change the ship recycling industry when they come into force. From both ship owner and ship recycling yard perspective, regulations change the requirement of the stakeholders, however, the biggest role in the new regulations belong to ship recycling yards as these regulations require to operate from built structures, to establish procedures and techniques to minimise, reduce, prevent the hazards and risks, systems to control any leakages. Therefore, new regulations require some changes in the operation towards safer operating procedures resulting in a facility that will require serious investments in the ship recycling yards. In addition to investments, the running costs of the yards will also increase (extra costs from the HSE measures and safe operating procedures). In order to compensate the investments and increased costs, ship recycling yards need to increase their revenue from the end of life ships or decrease the costs of the dismantling operations through various measures.

These regulations will also have an impact on the “green” ship recycling yards that managed to be registered in the European List of Ship Recyclers (European Commission, 2016). Currently the operating cost of these yards are higher compared to sub-norm yards due to the higher HSE related costs and worker costs. However, these new regulations can be considered as an opportunity for green yards as the costs of the yards in South Asia will increase which will make the competition with the yards in these countries easier. If the costs of the green ship recycling operations can be reduced and the profit can be increased (without compromising on the HSE) green ship recycling yards can become more competitive.

The ship recycling Industry is currently going through a transitional phase and therefore scientific support and technical approaches are needed more than ever before. However, the review of the literature showed that within the extant body of literature there are very few studies (Creese et al., 2002, Ahluwalia and Govindarajulu, 2005, Adamides et al., 2006, Alkaner et al., 2006a, Pylarinou et al., 2008, Koumanakos et al., 2006, Pylarinou et al., 2006) that focus on optimisation of the ship recycling facilities (The overview of the literature review can be found in Appendix A). There is a need for a reliable and easy to use methods to optimise the productivity of the ship recycling yards. Optimising the ship recycling processes will not only decrease the costs, but it will also increase the output of the yards, increase the earnings and in the long term, it will increase the capacity of the yards. Moreover, proving that the green ship recycling yards are still profitable, this might become an incentive for the industry to improve the operations.

Productivity issues are common in manufacturing industries and in order to survive in this fierce competitive environment it is important to understand system behaviour and the parameters that affects a system’s performance (Harrell and Tumay, 1997, Woo and Oh, 2018). The activities in most of the manufacturing industries are complex and dynamic, therefore in order to represent these activities a model is necessary (Neelamkavil, 1987). Models are used to identify, understand and address a wide range of issues in system design and operation of manufacturing industries; therefore, models are useful tools in addressing the production problems (Banks, 2005, Ljubenkov et al., 2008, Mousavi, 2011). One of the most powerful modelling techniques to investigate the performance of industry plants is simulation. The review of the literature showed that researchers used modelling and simulation tools commonly to address the productivity problems and to optimise the way their facilities, services and operations in manufacturing industries, shipbuilding yards, and other similar industries (e.g. electronics recycling) operate (Banks, 2005, Altiok and Melamed, 2010, Rossetti, 2015). Therefore, a similar approach is needed for the ship recycling industry. Simulation studies in the literature (Section 2.3) for ship recycling focus on the simple calculation of cost and revenue but do not go into the detail of improving the situation or addressing any productivity issues. Similar studies exist in the literature for the maritime industry (shipbuilding yards, port operations and maritime operations). However, this approach has not been applied to the ship recycling industry, as it requires extensive data, complexity of the ship recycling process and modelling. Development of such method can benefit the industry in many ways:

1. processes can be optimised for increased productivity and efficiency as well as lower costs (Law and Kelton, 1991, Banks and Gibson, 1997, Shin et al., 2004, Song and Woo, 2013, Woo and Oh, 2018),
2. possible effects of the investments such as new machinery, new layout, capacity increase etc., can be assessed before making the actual investment (Pegden et al., 1995, Shannon, 1998, Hosseinpour et al., 2009, Van der Aalst et al., 2010),
3. through the simulation, competitiveness of the European-norm ship recycling yards can be increased while maintaining high level of HSE standards.

Detailed discussion of the the simulation theory, when to use the simulation, benefits, and steps of simulation as well as the suitable computer tools to utilise in order to model the ship recycling processes have been summarised in Appendix B of this thesis.. In the next section, layout development, simulation and optimisation studies in the ship recycling and similar industries have been reviewed and discussed.

2.3 Review of Layout Development and Optimisation Studies in Ship Recycling and Similar Industries

The primary investigation of the ship recycling industry including the literature demonstrated that the industry needs a methodology to design and optimise ship recycling yards with specific focus on productivity. Simulation approach is commonly used in similar industries to overcome productivity challenges, therefore, simulation can be used for the design and optimisation of ship recycling yards as well. This section reviews the studies on the simulation and modelling of ship recycling yards as well as the simulation studies and approaches in similar industries that can be implemented to the ship recycling.

2.3.1 Review of Studies on Process Optimisation / ship recycling yard design

As mentioned before, studies that focus on simulation studies or process optimization of the ship recycling yards are very limited. Simulation studies require extensive data and the required data to conduct simulation study for ship recycling do not exist. This is due to the fact that the ship recycling industry is not very organised and operational data is not collected by the yards, hence, the data from the industry is not available to researchers. Therefore, studies on the modelling and simulation are limited. Existing simulation studies in the area of ship recycling are summarised in Table 2.3.

Table 2.3: Studies on simulation

Title	Year	Author(s) / Partner (s)	Aim(s)	Main Outcome
SHIPDISMANTL PROJECT	2005 - 2009	Naftosol; Uni. Patras, Indian Institute of Technology, Medimetal, Leyal, Strathclyde; Kingston Consultancy	Developing guidelines for operations, design, optimisation with respect to OHS&E, cost and energy and a DSS	Simulation based decision support, detailed HSE analysis,
A software tool for disposal of obsolete vessels	2005	Rasphal Ahluwalia, Sriram Govindarajulu	Estimation of costs, to view the inventory, construction details and to determine the petroleum products.	Tool to estimate cost of operation, material
A simulation based support decision support system for the dismantling of obsolete vessels	2006	Dimitrios Koumanakos, Charalambia Pylarinou, Antonios Hapsas, Nikos Karacapilidis, Emmanuel Adamides	Supporting decision making of ship recycling industry stakeholders	Decision support tool for ship dismantling stakeholders
Facility Layout Development for Ship Dismantling Facilities	2006	Selim Alkaner, Purnendu K. Das, D. Smith	Developing a design for the best facility layout alternatives	Generic layouts for ship recycling yards and layouts
An Integrated Information System for Supporting Lean and Green Ship Dismantling	2006	Emmanuel Adamides, Nikos Karacapilidis, Charalambia Pylarinou, Dimitrios Koumanakos, Antonios Hapsas,	Supporting green and lean ship recycling through the developed interconnected software tools that support the process design	Tool for process design
Integrating Simulation Into a Web-Based Decision Support Tool for The Cost Effective Planning of Vessel Dismantling Processes	2008	Charalambia Pylarinou, Dimitrios Koumanakos, Antonios Hapsas, Nikos Karacapilidis, Emmanuel Adamides	Supporting decision making of stakeholders on qualitative issues such as the appropriateness of a disposal methodology or the level of the safety of the workforce in a specific dismantling yard.	Decision support tool to support stakeholders on method and safety
A Web-Based Decision Support Tool for the Planning of Vessel Dismantling Processes	2009	Nikos Karacapilidis, Hara Pylarinou, Dimitrios Koumanakos	Supporting decision making of ship recycling industry stakeholders	Web based tool for decision support during planning

The first study, ShipDISMANTL project (Cost-effective and environmentally sound dismantling of obsolete vessels) was the first EU funded-project that was focused on the ship recycling. The project was funded with 1.5m € under the 6th European Research Framework Programme (FP6, 2005-2009) (EC, 2016a). Two specific outputs of this project are worth mentioning in this section of this thesis. First output is the simulation based Decision Support System for ship recycling yards, which was developed as a concept. Second output is the developed layout variants and the scorecards to guide the yards during the development stage. Several publications were made by the researchers on these outputs (Adamides et al., 2006, Koumanakos et al., 2006, Pylarinou et al., 2009, Alkaner et al., 2006a, Pylarinou et al., 2008).

A simulation-based Decision Support System (Figure 2.6) for collaborative modelling and management of ship recycling processes was developed in the project (Adamides et al., 2006, Pylarinou et al., 2006). The presented system used EXTEND software (dynamic simulation) on web-based system and supported design, planning, execution and improvement of recycling processes (Adamides et al., 2006). The proposed system was able to share the information across ship recycling yards and other stakeholders (broker companies, third party delegates, environmental and energy related organizations). For example, a broker company could use the tool to find suitable yards for end-of-life ships or Third party delegates could use the tool to cross check the ship being dismantled with the capacity of the ship recycling yard in order to make sure it is dismantled in the correct way. Recycling site owners can simulate the recycling process to see costs and time allocated to the recycling of the ship. The tool simulates the recycling process according to input data from yard owners. As part of the tool, a generic ship recycling process, which consisted of nine main activities, was modelled and the user input could be inserted through the web interface. The model included responses such as resource utilisation, times and costs, therefore, it was possible to identify the critical activities and address the problems which will lead to cost effective solutions (Figure 2.7) (Koumanakos et al., 2006). However, even though the tool developed in the ShipDISMANTL project was a good starting point, the tool and the method have some deficiencies. First, ship recycling process model of the tool is not clear, and the activities included does not cover all the activities in the ship recycling yard. Furthermore the software does not provide the user the flexibility to change the order of the process or add new processes, also tool does not allow case-specific process optimization. The processes are pre-defined and user can only pick from the predefined list by the authors. Even though the tool helps to define the critical activities, it is not possible to work in detail in the critical activity; for example, if the secondary zone is identified as the critical zone, tool does not allow to specifically optimise the actions in the secondary area (e.g. cutting lengths, cutting methods etc.). Also, none of these studies had the application of the tool to an operating ship recycling yard as a case study. Therefore, the validity of the tool is not known. Moreover, tool does not take the effect of the shipyard layout into account in the simulation or analysis. The flow of the workstations, distance, and traffic in the yard were also not taken into account, which is an important criterion in the facility design and process optimization. Therefore, there is a need for a more flexible, transparent tool that considers the layout to optimize the process and the design of the yards.

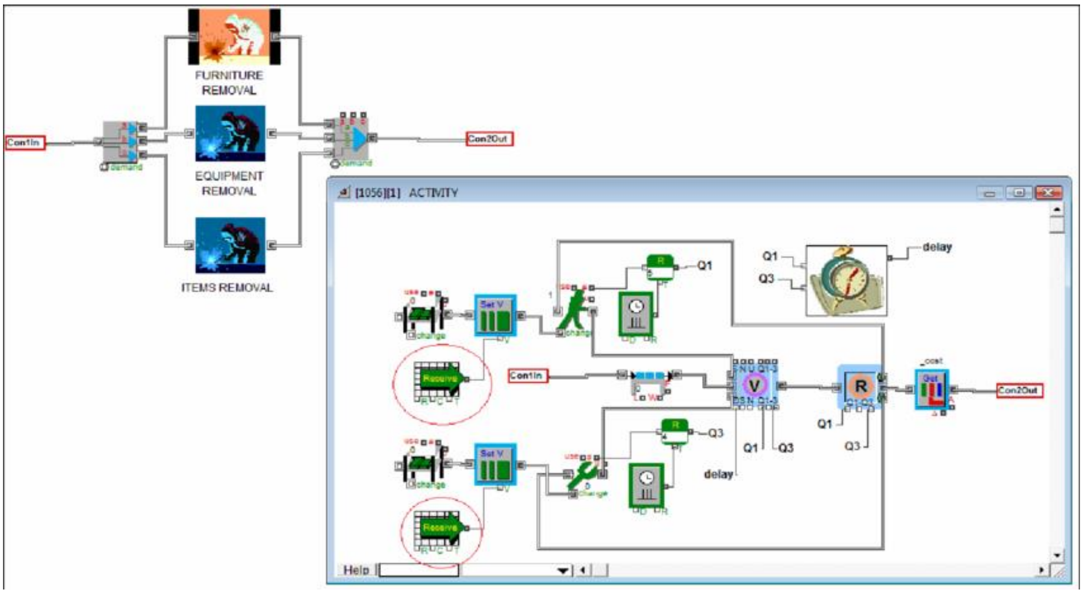
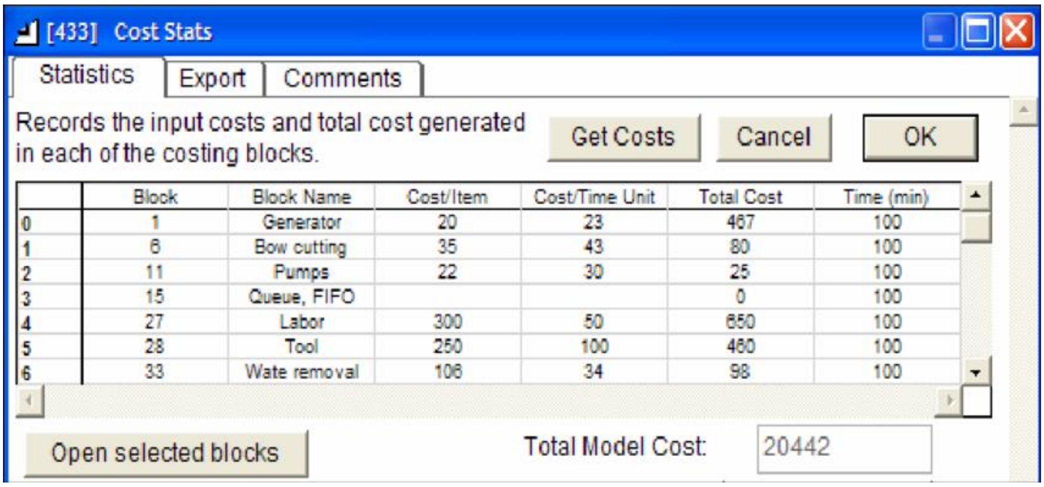


Figure 2.6: A part of the simulation model of Pylarinou et al. (2009).



	Block	Block Name	Cost/Item	Cost/Time Unit	Total Cost	Time (min)
0	1	Generator	20	23	467	100
1	6	Bow cutting	35	43	80	100
2	11	Pumps	22	30	25	100
3	15	Queue, FIFO			0	100
4	27	Labor	300	50	650	100
5	28	Tool	250	100	460	100
6	33	Wate removal	106	34	98	100

Figure 2.7: Example output of the Decision support tool developed by Pylarinou, Karacapilidis, and Adamides (2009)

As mentioned above, second important output of the ShipDISMANTL was the developed framework for ship recycling yard layout. Project systematically approached the shipyard planning taking the multi-dimensional and multi objective nature of the problem into account. Layout variants for generic case and the scorecards to guide the yards during the development stage were also generated for the case study (Alkaner et al., 2006a). A number of facility layout that represents typical combinations of modelling elements (primary zone, secondary zone, sea-shore interface, spill containment barrier, vessel) were developed in order to identify the best candidate facility (ShipDISMANTL, 2009, Alkaner et al., 2006a).

The developed layouts (Figure 2.8) were reviewed by the selected industry experts and eight layout variants were shortlisted. As a next step, further analysis was conducted by taking additional criteria (such as area need of layout, approach of vessel and applicability of layout to other cases) into account; these eight cases were further reduced to four variants. These four variants were for non-tidal beach, wet basin, pier, and dry-dock. These layouts were also combined with best suitable technology mix for primary and secondary cutting zones as the next step of the study. The layout development study of the ShipDISMANTL is the first in this area and the approach of the project to layout problem is unique using the layout design method of (Muther, 1973). Partners' idea of implementing Muther's design method to ship recycling can be followed but it should be improved by implementing the simulation into process and developing it as a step by step optimisation and design framework.

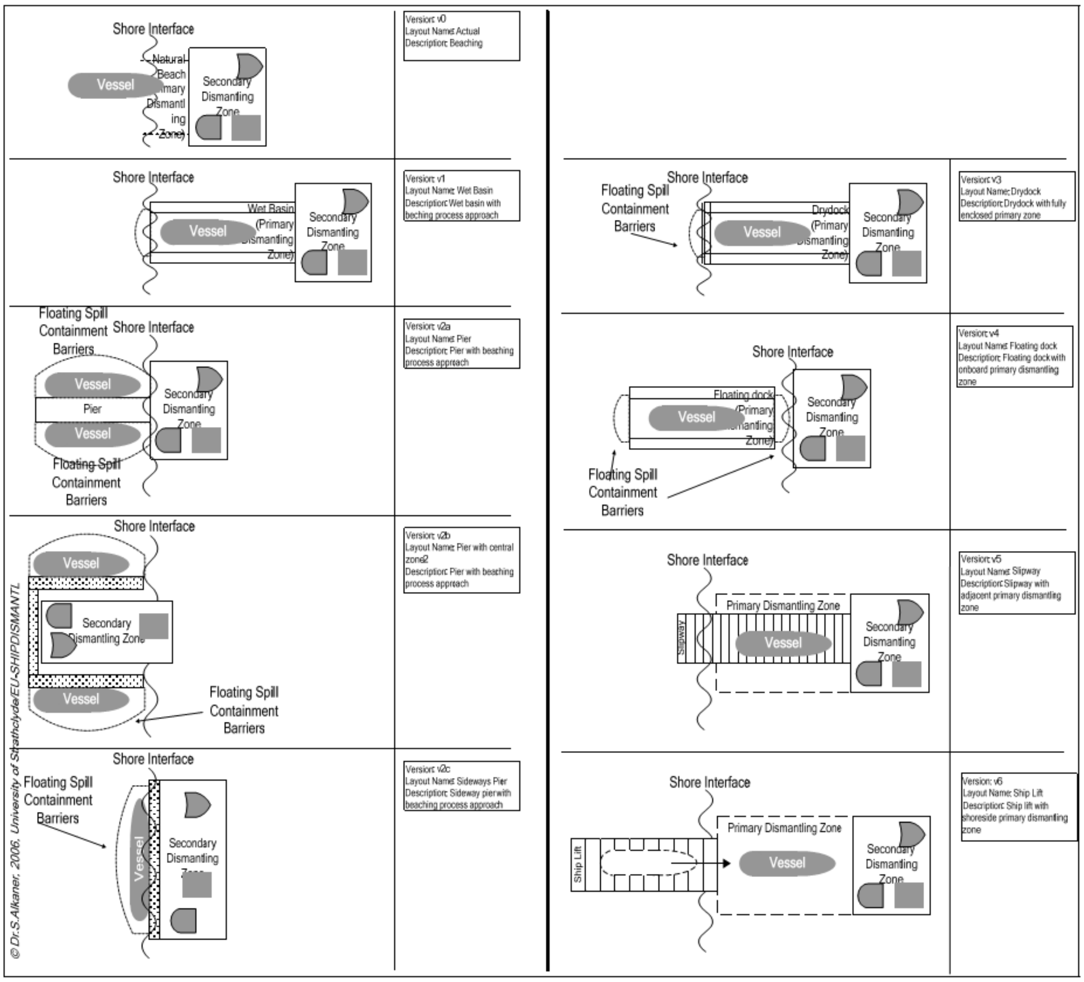


Figure 2.8: Ship recycling yard layout variants by Alkaner et al. (2006a).

This approach can be useful when developing yard layout and operation on each different case of ship recycling.

Apart from the tools and method developed in the ShipDISMANTL, Ahluwalia and Govindarajulu (2005) developed a web-based tool which can be used to estimate ship recycling costs, to investigate the inventory of ships, to investigate the construction details of a ship and to determine the number of petroleum products on board. In this research, authors developed a database containing information on obsolete vessels, cutting technologies, decontamination technologies, onboard petroleum products, recycling facilities in the US, towing companies and shipbuilders. The database was accessible through the web with authenticated username and password. Through the portal, information on the ship, cutting technologies and other information mentioned above were accessible. The program was using the methodology of Creese and Sibal (2001) and Creese et al. (2002) to estimate the revenue and cost of recycling a ship. Creese and Pooja (2001) explains the cost model developed by Maritime Administration (MARAD) to estimate the revenue and cost for recycling cargo ships. Three cargo ships were used to develop the model. In this model, revenue of the recycler was only considered as the sale revenue of the steel. Costs were divided into two categories as direct and indirect costs. Items of the direct costs were determined as direct labour, ship purchase, towing, personal protection, consumables, rigging and staging, asbestos removal, PCB disposal, tank and bilge cleaning, non-PCB disposal, cutting materials. Indirect costs were indirect benefits costs, overhead costs, general and administrative costs and bid and proposal costs. In this model, estimations were made using the previous MARAD data and these estimations were converted to be able to calculate with lightship weight tons. Creese et al. (2002) developed a second cost estimation method, The RAND model. While MARAD model was developed with the information on cargo ships, the RAND model was a parametric model which was developed using warships (which have more decks, compartments and equipment compared to cargo ships). In order to simplify the model, complexity model for ship type was presented for each ship type. The results of the MARAD and RAND model were extremely close. Also, results of the MARAD model were compared to real life examples and the results were very similar.

Even though the Creese and Sibal’s method is accurate, hence the programme was giving accurate results when compared to actual costs, the programme lacked the required flexibility. In order to address the needs of ship recycling industry more detailed analysis capabilities (such as testing of different resource combinations, different technologies, different layouts and zone allocations) are needed, which this software lacked to address.

In addition to the modelling and simulation studies, Jain (2017) also focused on increasing the competitiveness of the green ship recycling yards. Jain modelled the material flow of the end of life ships which is a good reference point to allocate the weight distribution and material flow from ships. (Jain et al., 2016, Jain, 2017, Jain et al., 2017). Jain's study can be utilised further to model the material flow within the yard through the case study.

2.3.2 Investigation of the Literature of Simulation Application in Maritime Industry and other Relevant Studies

The literature in the application of simulation in ship recycling is very narrow. However, as mentioned before, simulation is accepted as a valid tool to address the productivity problems in different industries including the maritime industry. Simulation approach is widely used in the maritime industry; areas include harbour operations, ship loading and off-loading operations, ship operations, shipyard operations/processes etc. In this section, studies in maritime industry, specifically on shipyards, and relevant studies (simulation on dismantling and recycling facilities) to the topic of this study were investigated and reviewed. As a conclusion, lessons learnt from these studies were summarized.

As mentioned above, researchers used simulation methods to work different maritime branches. For example, literature is very rich on the studies on the ports, container terminals, and ship operations to improve the efficiency, productivity and solve bottlenecks. These studies will not be investigated further as they are out of the scope of this thesis, but few are named below;

- El Sheikh et al. (1987), Gibson et al. (1992), Wadhwa (1992), Goldsman et al. (2002), van Asperen et al. (2003), Aksoy (2011), Shu and Zhang focused on the port optimisation,
- McCallum (1986), Teo (1993), Kia et al. (2002) focused on port design,
- Bruzzone and Signorile (1998), Merkuryev (1998), Tahar and Hussain (2000), Legato and Mazza (2001), Vis and Harika (2004), Parola and Sciomachen (2005), Laik and Hadjiconstantinou (2008), Alp (2009), Li

et al. (2009) and Esmer (2013) worked on the operation optimization of container terminals

- Koh et al. (1994), Gambardella et al. (1998), Sgouridis et al. (2003), Park and Dragovic (2009) studied container terminal planning
- Haralambides and Veenstra (2000), Bush et al. (2003), van Rengsburg et al (2005), McLean and Biles (2008), Fagerholt et al. (2010) applied simulation to ship/barge operations
- Canal operations, Franzese (2004), financial risk in ship investment (Gumus, 2013).

Apart from the operational area, simulation approach was used in the ship building industry. As ship recycling is often considered as reverse ship building (Alkaner et al., 2006b), simulation approaches for shipbuilding industry can provide an initial guidance on application to the ship recycling studies.

2.3.2.1 Simulation and Optimisation of Processes in Shipbuilding

Literature is quite rich for the simulation studies in shipbuilding industry. Woo and Oh summarised the application areas of simulation in the shipbuilding industry (Woo and Oh, 2018) which demonstrates the application range (Table 2.4) and the problems it can address in the shipbuilding industry. Similar approach can address the similar issues in processes in ship recycling yards.

One of the pioneers in the area, Odabasi, (Odabasi et al., 1997) used simulation to support the development, design and evaluation of shipyards' expansion programs. In this study, a small-scale shipyard was investigated. First the relation between the workshops in the yard was investigated and then different layout alternatives were tested in order to optimize the workshops. The relationship analysis used by the author is developed by Muther (1973) and this method can be applied to ship recycling yard to plan the layout of the yard. Alkaner (1998) developed and evaluated the potential use of a simulation models as a decision support tool for ship production. This research proved that the simulation modelling and analysis is feasible to be used in the decision making in ship building industry. Alkaner (1998) points out that collection of the collection of the production data is considered to be the most critical effort during the modeling stage of the system (Alkaner, 1998).

Table 2.4: Application areas of simulation in shipbuilding (Woo and Oh, 2018)

Process	Problems
Plate stock and arrangement	Lack of consideration of plate arrangement in stock yard when steel-plate order is processed Heavy work load for plate arrangement
Plate blasting	Lack of consideration of the cutting order; the blasting order is fixed regardless of the cutting order
Cutting	Unnecessary cutting and sorting works frequently occur, and the lead time of a specific block is increased owing to a lack of consideration of the sub-assembly sequenceLack of load balancing of each cutting bay
Piece (or Part) sorting	Excessive sorting works due to the increase of pieces in stock lead to the shortage of stock areaLack of consideration of sub-assembly pattern leads to the inappropriate allotment of pieces
Sub assembly	Assembly pattern drawn by the design department is not in accordance with shop floor conditions Work load is not balanced at the assembly line because the work volume is calculated based on welding length alone Workforce assignment is not well established because the work load is unbalanced
Unit and grand assembly	Lack of objective data for shortening production cycle timeControl at the management level is difficult owing to excessive manual work at shop floor
Block inspection, outfitting and painting at outdoor yard	Difficult to estimate the work load of each workstage outdoor yardLack of transporter planningDisconnection between production plan and logistics

Shin et al. modelled and simulated (Figure 2.9) the production process (base joining, piece alignment, tack welding, and robot welding) in subassembly lines at a shipyard (Shin et al., 2004). Authors first analysed the system then modelled using discrete event simulation method and using the approach developed by Shin (Shin and Sohn, 2000, Shin et al., 2002) to investigate the productivity and efficiency of the line. In the model, different variations of resources were tested and 26% increase of productivity was obtained through the implementation of new technology (welding robots) (Shin et al., 2004). This study is a good example of implementation of alternative methods to improve the current situation in the facility.

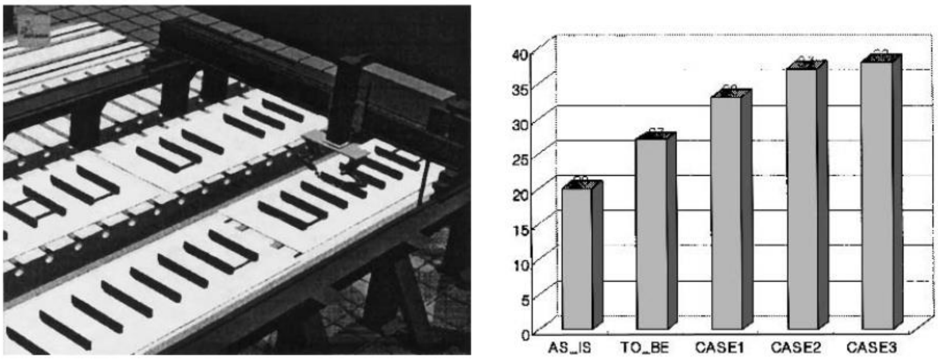


Figure 2.9: Simulation model developed by Shin (left) and the output of the system (right) (Shin et al., 2004)

Shin et al. (2009) carried out another study to develop a framework for the layout design of shipyards and applied the systems engineering framework guided by SO/IEC 15288 is applied during the planning stage of the shipyard layout (Figure 2.10). Authors also integrated the simulation into the design in order to find the effectiveness of the developed layouts (Shin et al., 2009). Systems engineering approach on the planning stage of the yard (using SO/IEC 15288) can be used in the design of ship recycling yards and implemented with simulation.

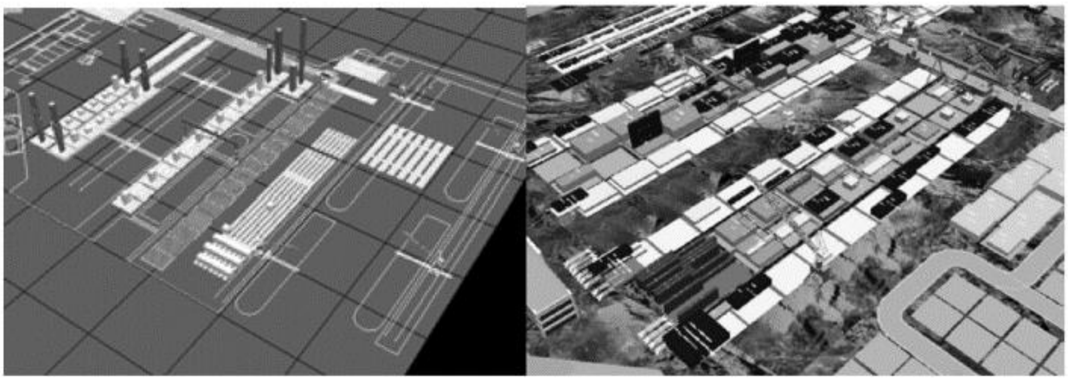


Figure 2.10: Computer simulation for production planning validation (left side: simplified simulation, right side: detailed simulation Shin et al. (2009).

Greenwood et al. (2005) presented a decision support system for a panel shop which was the bottleneck of a shipyard, where the Decision support system utilised discrete event simulation models to optimise the operation in the panel shop. In this study, operations in the panel line was simulated through ProModel software and system was optimised by implementing several changes (number of workers, personnel and machine effectiveness. Similar approach can be followed for ship recycling industry after the successful development of simulation approach.

Hadjina suggested a simulation based modelling approach for shipbuilding production process design. The simulation and modelling approach to a real robotized profile cutting process line within specific shipyard production process is demonstrated and 25% of improvement was achieved in the overall cutting time of the panels (Hadjina, 2009). Cutting methods applicable to ship recycling industry can also be investigated and the impact can be tested with simulation similar to Hadjina's study.

Lee at al. simulated the panel block assembly shop in a shipyard to address the bottlenecks in the production and carry out a materials flow analysis to maximise the productivity (Figure 2.11). The model was validated with real scenario and developed system for panel simulation can provide the most feasible schedule with respect to deadlines, resource capacity and material availability (Lee et al., 2009). This study shows that materials flow is important in the simulation studies, for example the amount of material transferred between the stations is a key parameter for both transport allocation and area allocation and should be taken into account.

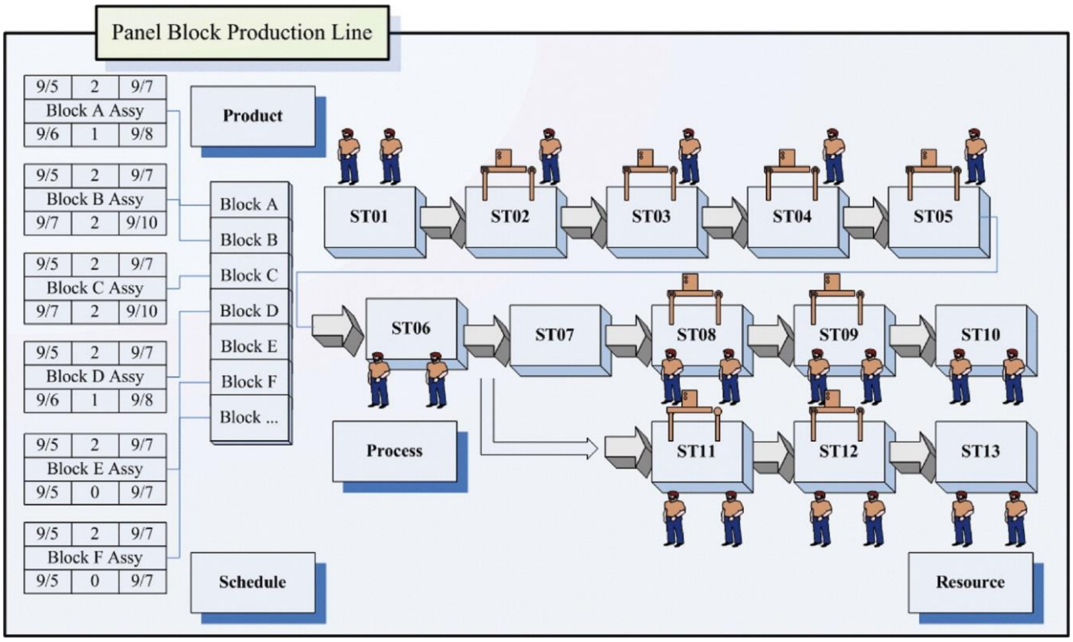


Figure 2.11: Representation of Lee's simulation model (Lee et al., 2009).

Caprace also worked on Discrete Event Simulation (DES) and optimization of ship yard activities (Caprace et al., 2011a, Caprace et al., 2011b). In this study, Caprace et al. (2011) first reviewed available DES software to find the best option using analytical hierarchy process, then a block erection were simulated for two different blocks assembly options.. Using the same amount of resources, 18% of decrease in lead time was achieved. The approach of Caprace on block assembly can be reversed and adapted for ship recycling and different disassembly simulations for blocks can be conducted.

Ozkok conducted several studies in different stages of ship construction to improve the ship construction process (Ozkok, 2010, Ozkok, 2012, Ozkok et al., 2011, Ozkok and Helvacioglu, 2013). Ozkok implemented the discrete event simulation method to a shipyard through ARENA discrete event simulation software as part of his thesis and as a case study, double bottom block of a container ship was selected (Ozkok, 2010). The main aim of this study was to decrease the cycle time in the selected panel line and ARENA to optimize the production. First the problems causing the delays were identified as presented in Figure 2.12 then alternatives to overcome the identified issues were addressed. In different studies, Ozkok studied different variations of his method; In 2012, he studied the effect of matrix module assembly on panel line in a shipyard (Ozkok, 2012), in another study, Ozkok focused on double bottom block construction (Ozkok and Helvacioglu, 2013), and lately profile cutting activities in a shipyard (Ozkok, 2017). In one of the studies, authors used Ishikawa diagram (a.k.a. fishbone diagram) to identify the root causes of the problems and addressed these problems using the simulation (Figure 2.12). Same method can be applied to ship recycling yards to identify the problems on productivity and to identify the case studies.

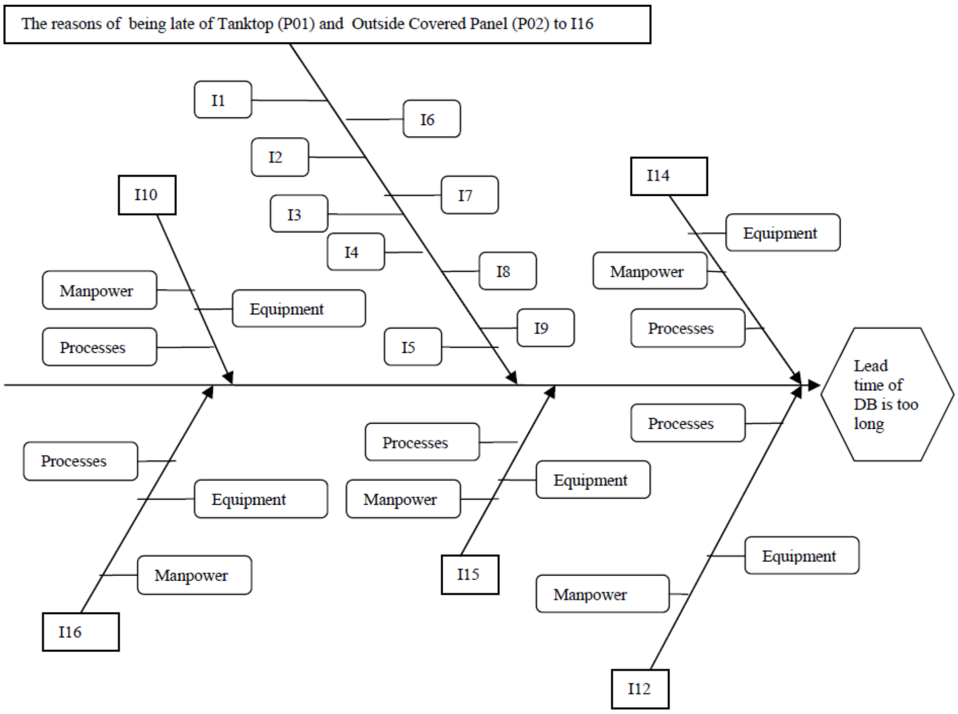


Figure 2.12: Cause-effect diagram (Ozkok and Helvacioglu, 2013)

Goo et al. (2013) used DES framework to plan the ship building and organize the scheduling of the construction. Shipbuilding is a complex business and the construction of a vessel has complex steps. Modelling these complex steps are difficult, therefore authors used the layered modelling (Figure 2.13). The DES model proposed by authors, produces accurate results to verify performance and scheduling of the yard (Goo et al., 2013). Since ship recycling industry is also similar, with complex procedures, which are difficult to manage, simulation models can be divided into sublevels and submodels.

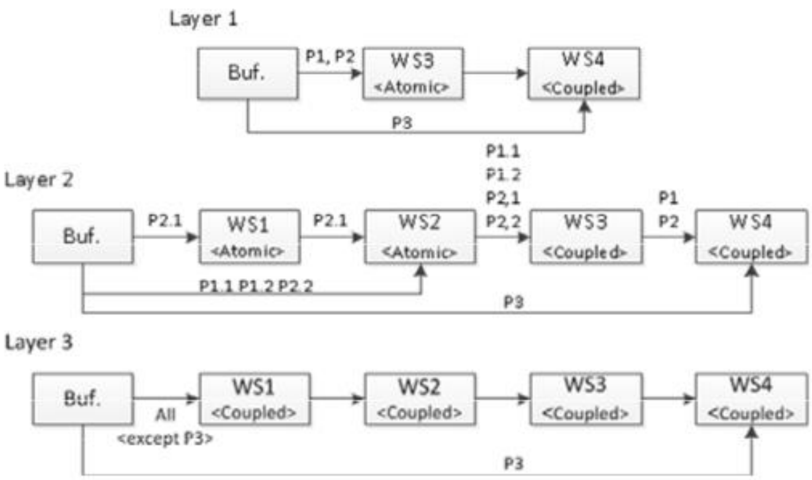


Figure 2.13: Example structure of sub-layer models (Goo et al., 2013)

Cebral-Fernandez et al. (2017) using discrete event simulation and ExtendSim, simulated three case studies to obtain and validate model that can be used in shipbuilding process (Figure 2.14). Model was proven to be useful for decision making at early planning stages of the projects and to improve the production schedule with more accurate time planning. In addition, model was also useful to identify the bottlenecks and analyse the changes in the cutting and welding workshop (Cebral-Fernández et al., 2017). Using the simulation, the authors identified the effect of resources on the production and obtained the minimum time using the minimum number of resources, as well as the maximum capacity of the panel line.

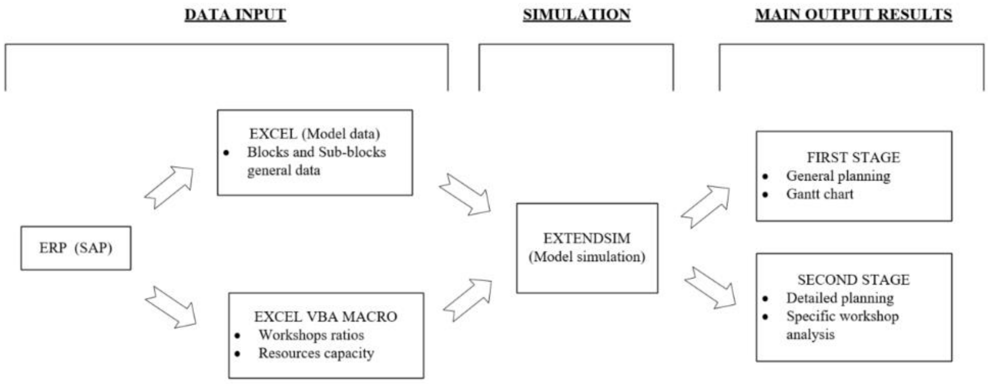


Figure 2.14: Simulation process flow (Cebral-Fernández et al., 2017).

Even though studies on ship building simulation provides a good starting point, these simulations are based on the assembly process of the different materials. However, as a nature ship recycling is the reverse of the assembly process. Therefore, studies on the other dismantling and recycling industries should also be investigated.

2.3.2.2 Simulation Studies in Other Dismantling/Recycling Industries

Apart from the studies in shipbuilding, other recycling studies can also help with the modelling of the ship recycling operations. In this section, selected studies that were focused on the recycling simulation were summarized.

Hesselbach and Westernhagen also studied Waste Electrical and Electronic Equipment (WEEE) dismantling and a software-tool to support the planning of disassembly process, optimize their disassembly processes and improve the productivity in recycling electrical scrap (Hesselbach and Westernhagen, 1999). This paper shows the importance of the layout in the disassembly facilities as the reverse material flow is more complicated compared to the flow in the manufacturing industry. Therefore, layout design and the simulation should be considered together.

Capraz also used simulation approach for layout planning in e-waste recovery systems (Capraz, 2013, Capraz et al., 2017). First e-waste disassembly system and processes were investigated then alternative layouts were developed and assessed with DES software. The developed models were compared based on performance criteria (e.g. recyclable fraction quantity from disassembly operations, the total number of disassembled e-waste products, total revenue from the sales of recyclable fractions, and the time spent for non-value-added activities) (Capraz, 2013, Capraz et al., 2017). The approach of the author proves the usefulness of simulation tool for the recycling operations and demonstrates the use the simulation tools on how to build a demanufacturing simulation model.

Limaye focused on the simulation and modelling of electronic demanufacturing facilities (Limaye, 1999, Limaye and Caudill, 1999). In his thesis Limaye built a demanufacturing simulation model to compare different options for operations, resource and layout changes. (Limaye and Caudill, 1999). This thesis is a good reference point for ship recycling studies as the authors demonstrate the model building for demanufacturing facilities (Limaye, 1999). Moreover, the authors also create (drag-in) model templates for future use through the simulation tool. Similar approach can be considered for ship recycling so that the yards can create their DES models without extensive model building knowledge.

Apart from the aforementioned recycling studies, End-of-Life Vehicle (ELV)'s are a major waste stream in EU (COMMISSION, 2012). EU has identified the ELVs as priority waste stream in the early 1990's (Simic, 2013) which motivated the researchers to work in this particular area. Simulation approach has also been used in the ELV recycling. Sim et al used DES to compare four different disassembly methodology of cars (Sim et al., 2005). Sim et al. first analysed the existing disassembly systems for cars, and then alternative systems were designed to overcome the bottlenecks. After the data collection, simulation were completed (Figure 2.15) and based on the results, four alternatives to improve performance of the system were proposed.

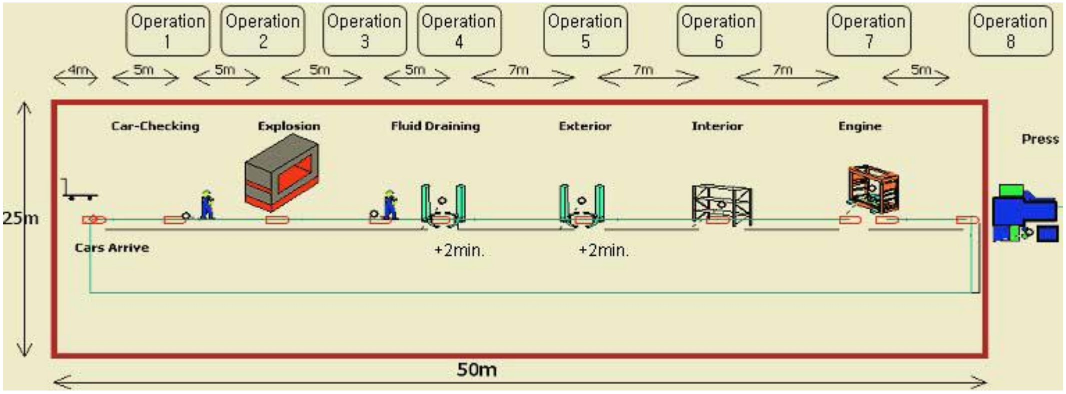


Figure 2.15: ARENA simulation model (Sim et al., 2005)

Zhang and Chen, (2018) analyzed and optimized the disassembly processes and productivity of a disassembly line with DES. Zhang and Chen first developed a system model of the disassembly line (Figure 2.16), and then simulated the four different scenarios to test different conditions to see whether the system will reach the final goal of 30000 cars dismantled annually. After the simulation, the developed scenarios were discussed for advantages and disadvantages. Simulation has revealed satisfying productivity in the analysis of the disassembly facility in this study. According to the authors the assumptions included in the simulation model have to be considered carefully (Zhang and Chen, 2018) and same applies for ship recycling. Authors applied the methodology for the dismantling of specific car to eliminate the complexity of the simulation. Same approach can be followed in the ship recycling simulation and a case study ship can be selected to eliminate the uncertainty from the simulation.

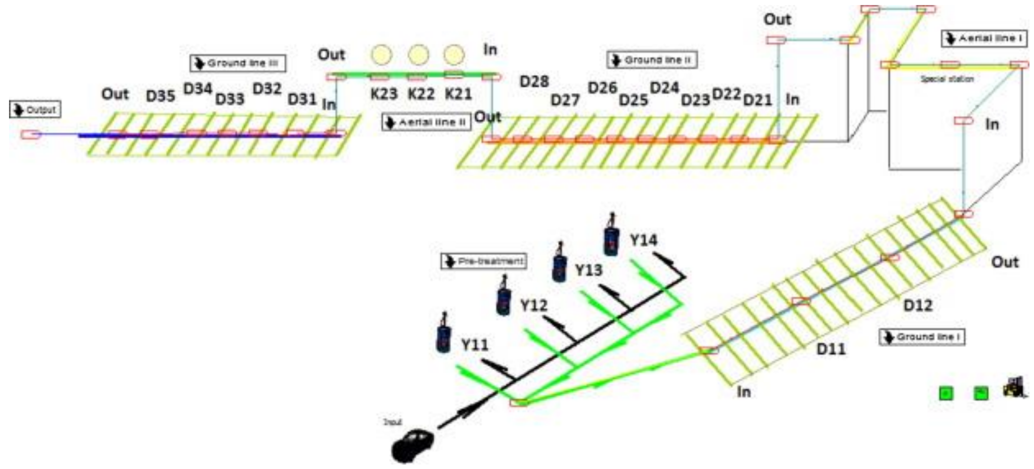


Figure 2.16: ARENA based model layout of the disassembly line (Zhang and Chen, 2018).

2.3.2.3 Lessons learnt from the shipbuilding simulation studies and recycling/decommissioning simulation studies.

This section will summarise the lessons learnt from the literature in the shipbuilding and recycling/decommissioning. These implications gained from the literature will help build up the methodology, models, parameters and the case studies.

- Shipbuilding is a very complex business and the construction of a vessel has complex steps. Modelling these complex steps are difficult, and without use of sub-models (Goo et al., 2013), simulation ends up being too complicated and hard to understand for the user/modeller. In the shipyard studies, researchers divided the shipyard to specific workshops (subzones) and first modelled these subzones, then they moved to the bigger picture. Given the complexity of ship recycling, similar approach should be followed for ship recycling industry. The simulation should be broken down to small steps and each step should be modelled individually.
- It is important to analyse the ship recycling process in detail with resource required for each step along with the data required to model the step. During the initial investigations, a process flow diagram with resources involved can be drawn for easier understanding (Hesselbach and Westernhagen, 1999, Limaye, 1999).

- Material flow is important in both shipbuilding and demanufacturing industries (Hesselbach and Westernhagen, 1999, Lee et al., 2009) and it should be modelled as accurate as possible. Therefore, access to a ship with known end-of-life ship is important for the success of this initial study.
- During the shipbuilding modelling, authors have created frameworks with flexible process flows that can be modified for each yard as every yard and every ship is unique. Same approach should be followed for the ship recycling industry (Shin et al., 2004, Hadjina, 2009, Woo and Oh, 2018)
- Layout development is an important part of ship recycling yard design. Layout development methodologies (process flow, area allocation, relation matrix, etc.) used in the academic studies can also be implemented to the ship recycling yards (Hesselbach and Westernhagen, 1999, Limaye, 1999, Greenwood et al., 2005, Hadjina, 2009)
- In the ship building, researchers modified the cutting/welding stations to optimize the production and succeeded improvements up to 40% in the production times (Shin et al., 2004, Hadjina, 2009, Ozkok, 2010, Caprace et al., 2011a, Caprace et al., 2011b, Woo and Oh, 2018). As one of the most dominant activity in ship recycling yards is cutting (Kurt et al., 2017), similar approach can be followed for ship recycling industry and cutting activities can be focused on.
- Ishikawa diagram (a.k.a. fishbone diagram) can be applied to ship recycling yards to identify the problems with productivity (Ozkok and Helvacioglu, 2013).
- Assumptions are essential in order to prevent complexity and uncertainty of the systems in modelling but these assumptions on the simulation model have to be done correctly and assumptions should be able to reflect the actual system accurately (Zhang and Chen, 2018).

2.4 Chapter Summary

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

Chapter 3 Research Question, Aim and Objectives

3.1 Chapter Overview

Extensive review of the literature helped the author of this thesis to understand the status of ship recycling and to identify the areas that require further attention. This chapter represents the identified gap and defines the research question, aims and objectives that will be addressed in this thesis.

3.2 Research Question

There is a need to develop a framework to systematically design green ship recycling yards to optimise the productivity and increase operational efficiency. In this way, new ship recycling yards, which have higher investment requirement and operational cost compared to the subnorm yards, can be designed. Moreover existing yards can be strategically improved so that they can compete with the non-compliant ship recycling yards. Therefore, the research question that the author aims to answer in this PhD study is;

“Can we develop a simulation framework to assist the development of efficient ship recycling yard designs and procedures?”

3.3 Aim & Objectives

The main aim of this research is to support the development and enhancement of ship recycling yards by developing a framework in order to improve the efficiency of the ship recycling yards through implementing discrete event simulation methodology. This aim will be achieved by fulfilling the following specific objectives;

- To investigate discrete event simulation method and to select most appropriate software package for this study
- To review and investigate typical ship recycling processes adopted in different countries where necessary conduct field studies in order to investigate process and material flow
- To build ship recycling yard procedures and process models in Arena simulation environment
- To identify the required data for the developed models and to conduct a detailed data collection study to successfully conduct the simulation
- To develop a framework for the design and optimisation of ship recycling yards based on the simulation models
- To develop layout alternatives for a ship recycling yard and assess the performance of these layouts using simulation
- To conduct case studies which focus on alternative cutting technologies to improve the efficiency and profitability of the ship recycling yards.

In order to reach this aim and achieve the specific objectives, fully functioning ship recycling yard models needs to be developed for different ship recycling methods. These developed models need to be flexible and applicable to any ship recycling yard at micro (workshop or zone) and macro (facility-wide) level. Moreover, these models can be used to compare the existing ship recycling methodologies (e.g. ship recycling yard layouts, docking scenarios, capacity scenarios) with alternative “What if?” scenarios.

3.4 Chapter Summary

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

Chapter 4 Ship Recycling Process and Development of Simulation Model

4.1 Chapter Overview

This chapter first investigates and summarises the operation procedures in different ship recycling countries. Operating procedures in different ship recycling countries were then compared and a standard ship recycling process flow is developed. Finally, simulation approach for the standard process flow is summarised in this chapter.

4.2 Data Collection and Field Studies

This PhD study aims to deliver a novel simulation framework, which is equipped with realistic process models and accurate process data. Accuracy of the simulations and reliability of conclusions directly depend on the success of data collection and data process. Therefore, it was highly essential to conduct field studies and data collection campaigns as part of this PhD study. Hence, significant amount of time was dedicated to field studies, observations and expert consultations to be able to create simulation models as close as possible to the real-world examples.

4.2.1 Methodology

Considering the importance of data collection in this PhD project, approach for data collection was carefully considered and planned in a way to overcome existing barriers towards obtaining data. In most of the cases required data either did not exist, or not shared with the researcher due to sensitivity of the yard. As a result, the following approach was used to collect or create the data that is required for the analysis in this PhD study.

First, observation studies were planned to create the inventory of ship recycling procedures from numerous countries. Then, more detailed data collection studies were planned in order to create or collect production data. Especially time-motion studies were employed to observe and quantify process times. Finally, cost data and other missing data that could not be obtained during the field studies (e.g. process times, procedures) were obtained through expert consultations, which were organised in terms of structured surveys, interviews and workshops. The amount of data collected from field studies and know-how transferred from experts can be considered as a major contribution as such data, which has never been available at research domain. Details of the different data collection and field studies are given in the following sections

4.2.2 Observation studies

Observation studies were concentrated on capturing the actual step-by-step procedures followed in the ship recycling yard when dismantling a vessel. Yard plans were obtained and specific zones were identified to group certain types of production together. Then material flows were observed generally starting from primary zone where the ship is located. Materials then followed until they leave the yard or reached to storage locations. All procedures and associated resources were recorded.

Another aim for observation studies was to capture production problems in the ship recycling yards. For example, during these observation studies bottle necks in the yard that limit the production speed has been identified. Identified problem areas were then utilised to develop case studies and propose alternative technologies for production.

Following sections will describe the details of each observation study conducted in this PhD project.

4.2.2.1 Observation study in Bangladesh

An observation study in Bangladesh was conducted for two weeks between 4-17 October 2015. During this observation study, five different ship recycling yards were visited to capture the ship recycling process in detail. Step-by-step process flows were mapped during the visits and material flows were observed and recorded. In addition, yard plans were obtained during this observation study. Detailed results and comments of this observational study were shared in Section 4.3.1.1 below. Some example photographs taken during the observation study are given in Figure 4.1, Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5

Figure 4.1: Pictures from the yards in Bangladesh

Figure 4.2: Pictures from the yards

Figure 4.3: Secondary cutting operation and material handling

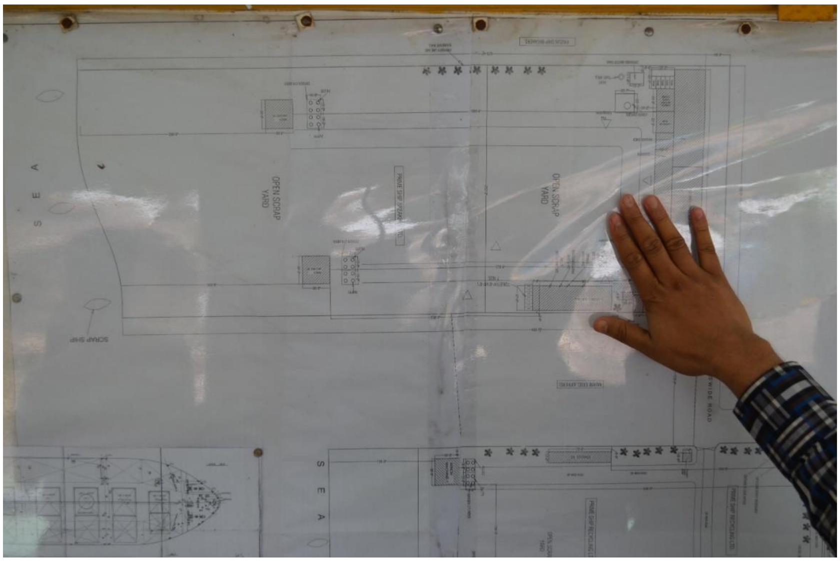


Figure 4.4: Layout of the visited yard

Figure 4.5: Machinery waiting to be sold in the storage zone

4.2.2.2 Observation study in Turkey

Similar to previous section, an observational study in the Turkish Ship breaking zone in Aliaga was conducted between 2-3 September 2014. Turkish ship recycling yards implement a different method compared to Bangladesh for dismantling (i.e. landing method), and therefore, this observation study targeted to develop detailed process model for the landing method (Figure 4.6). As a result, all procedures and material flows were witnessed and the process models were recorded from these observations. Final process models were given in Section 4.3.2.

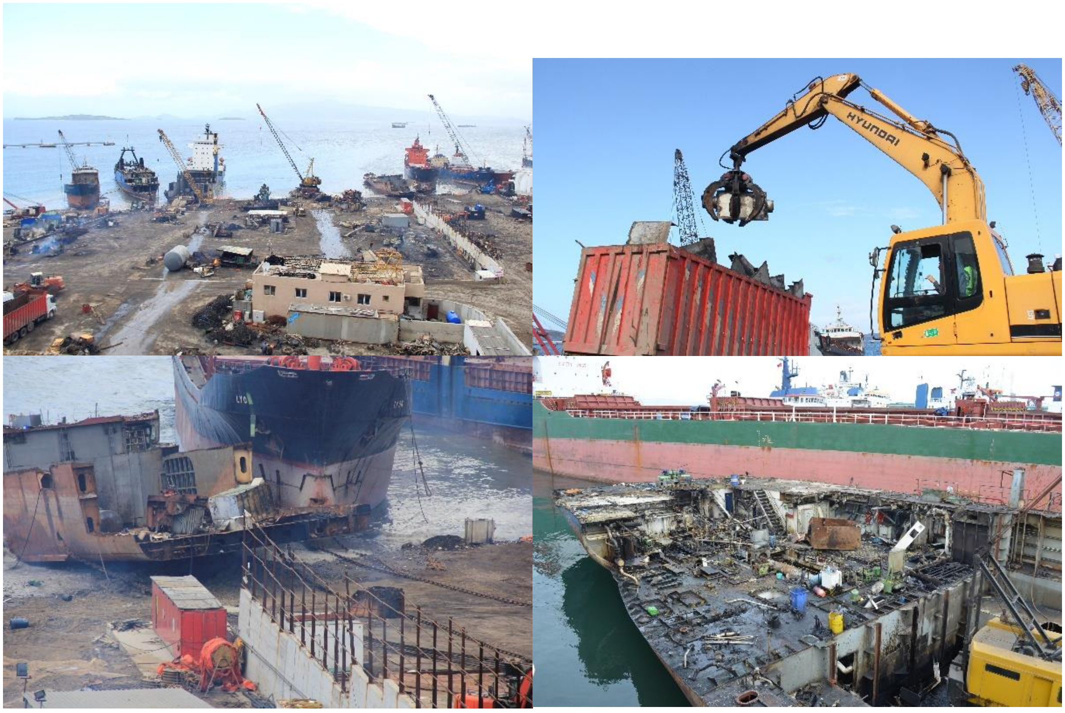


Figure 4.6: Pictures taken in the Turkish ship recycling yards

4.2.2.3 Observation study in Spain

Following the same approach, an observation study was also conducted in Spain to capture the step-by-step procedures, which are followed in the Spanish ship recycling yards during the dismantling operations. Spanish yards generally focus on dismantling smaller ships and they are required to operate under European laws. Therefore, the procedure followed in these yards may be different from the yards in Asia. For this reason, this observation study was conducted to ensure that developed process models were applicable to European yards. The outcome of this observation study was used to support the process model in Section 4.3.2 and case study in Section 6.2.1.2 and Section 7.2.

Figure 4.7: Pictures taken in the Spanish ship recycling yard

4.2.2.4 Observation study in France

A field study was conducted in Arzal, France to collect data on the dismantling of boats and recreational crafts between 24 November 2014 and 28 November 2014. During this field study, the overall process for dismantling a small-sized sailing yacht was observed, and the process and material flows were recorded (Figure 4.8). Cost and operational data were also gathered together with the observations. Overall, this observational study provided an important insight from the boat dismantling perspective. However, since the size of the boats dismantled in the yard were too small and the procedure involved in dismantling obsolete recreational craft was significantly different than the procedure followed for dismantling commercial ships, it was decided that recreational craft dismantling was going to be excluded from the scope of this study. Therefore, observational study findings and collected data were not utilised in this study. However, techniques used to dismantle fiberglass can be utilised to handle the fibreglass materials recovered from commercials vessels.

Figure 4.8: Example photos from the boat dismantling process

4.2.3 Time-motion study

Detailed process models were developed as a result of comprehensive observation studies described in previous section. However, in order to simulate these procedures in computer environment it was also necessary to obtain production performance data which was not readily available before. In order to create this data following strategy was adapted. Each process step in process models were specifically observed during yard visits. These procedures were recorded fully in videos while associated resources their technical details and running conditions were captured. These videos were then replayed at office environment and production speeds were calculated for each of the processes.

A field study was conducted in Aliaga Turkey, during which each process was recorded with a video camera. The field work lasted one week and especially steel cutting jobs, transportation and handling jobs were observed in detail. Figure 4.9 shows a snapshot from a video, which was captured during cutting in secondary zone. Each cutting line was measured, heating and cutting speeds were recorded (Figure 4.10). Detailed results of this time motion study are given in Appendix D: Data Collection.

Figure 4.9: Snapshot from the time motion study:

Similar video-based time motion study, which was conducted in DIVEST Project, was also available for the use of this PhD study. Therefore, DIVEST project's videos were also obtained and analysed from scratch by following the same strategy to enhance and detail the performance data created in this project.

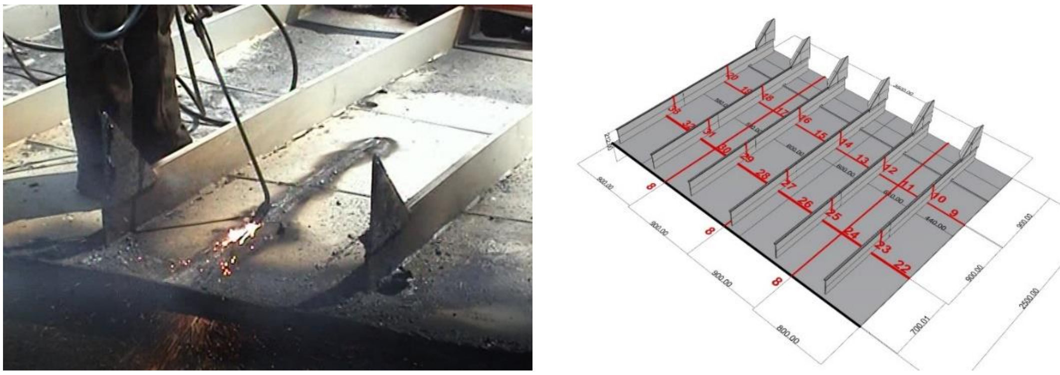


Figure 4.10: Procedure followed for time-motion study

4.2.4 Expert consultations and structured interviews

As some of the operational data was missing due to the lack recording practice in ship recycling yards (especially historic data which cannot be created easily), it was necessary to seek expert opinions to generate these data. Therefore following two methods were performed: (1) expert workshops (2) structured interviews.

4.2.4.1 Expert workshops

An expert workshop was conducted in Bangladesh on 10/10/15 during IMO SENSREC Project Field work. Workshop was hosted by Bangladesh Ship Breakers Association (BSBA) with 20 participants. The profile of these experts is given in the Table 4.1.

Table 4.1: Background of the experts and the number of participants from each category

Profile	Number
Local ship breaking experts	4
International ship recycling experts	4
Government agencies	4
BSBA	7
Other participants	1

In this workshop following information was obtained

- Ship recycling procedures
- Reasons and justifications for following certain processes
- Current problem areas that require attention

- Some of the cost data (steel rates, worker rates etc.)

4.2.4.2 Structured interviews

Workshop conducted in previous section was useful for shaping the case studies and alternative procedures tested in case studies. However, it did not provide detailed data that was required as an input for the simulations and other calculations. Therefore, structured interviews were conducted with a European ship recycling yard owner, Mr Antonio Barredo. The interview took place on 06/03/2015 in Naples, Italy. Template followed during this interview can be found in Appendix: D.

In addition to the interviews with Mr Barredo, additional questionnaire was also created and distributed to collect process data regarding the engine room dismantling. The questionnaires were sent to experts who have expertise in dismantling main and auxiliary engines. Questionnaire was distributed to a total of 25 experts out of which 11 responded. The detailed findings of this investigation study are given in Appendix D: Data Collection.

As a result of these interviews following data were obtained and used in simulations which are reported in case studies:

- Yard procedures
- Yard layout and physical limitations
- Owners requirements, commercial targets and expectations
- Various categories of cost data
- Legislative requirements
- Human resources
- Facility, tools, equipment and technologies
- Technical capacities of equipment and machineries (e.g. cutting and lifting equipment capacity)
- Capacities of storage and cleaning/treatment units

Data generated through these structured interviews were utilised directly in Chapter 6 and Chapter 7 in which the case studies were presented.

4.2.5 Additional Data Collection Activity

In addition to the observation studies in the field, further visits to Bangladesh Ship Breakers Association (10 Oct 2015), meetings with Ministry of Industries (on 06 Oct 2015), Department of Environment (07 Oct 2015) as well as local offices of ILO (06 Oct 2015) and IMO (on 07 October 2015) were organised to identify the problems within ship recycling yards. The information gathered in these meetings and interviews were utilised in the Section 5.6 of this thesis where the problems in the ship recycling yards were identified and discussed.

Additional field trip was organised to investigate the Indonesian ship recycling yards and it was concluded that process models developed in this PhD study can also be applied to Indonesian ship recycling practice by removing number of steps (such as approval by authorities, survey of the ship, and treatment of hazardous materials) from the generalised process steps.

Manufacturer data from the equipment (e.g. cutting technologies, polygrabs and cranes) in the yard were also obtained through contacting the manufacturers directly as well as the factsheets of the equipment.

Furthermore, academic literature was also investigated to identify potential sources of data. The investigation of the literature demonstrated that studies which report the step by step procedure clearly are very few. As DIVEST and ShipDISMANTL projects studied the procedure in detail, the investigation of these projects were used as a starting point. Furthermore, studies in the literature which also investigated the regional procedures were taken into account; (e.g. Hossain and Islam (2006) Shameem (2012), Ahammad and Sujauddin (2017) for Bangladesh, Sivaprasad (2010) and JICO (2017) for India, ILPI (2016) for Pakistan). Similarly, Jain (2017) reported a detailed material flow for a specific ship during dismantling procedures. According to the best of author’s knowledge, Jain’s material flow data is the most comprehensive available and can be utilised in this thesis.

4.3 Ship Recycling Processes

The main aim of this section is to analyse current ship recycling methods and create a step by step representation of each method. Then, different ship recycling methods will be compared to generate one standard ship recycling flow that can be modified and applied for all different ship recycling methods.

This analysis is divided into four headings according to docking types being used in the industry, beaching, slipway, quayside and drydock. In the next section, simple and detailed representations (which includes the processes and data requirement of each step) of the ship recycling procedures for each docking method are shared. These diagrams were used in order to create the generic ship recycling beaching model and to create the simulation model in Arena software. All diagrams shown in this chapter, uses the colour notation shown in Figure 4.11.

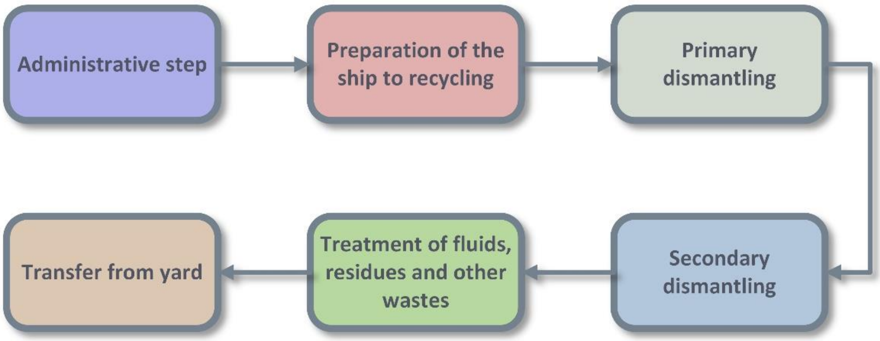


Figure 4.11: Generic representation of the process

4.3.1 Beaching

Beaching is the most common docking type (per volume dismantled) for ship recycling. Beaching method is the steering of end-of-life ship to the shore on the high tide using its own power. Following the docking operation, workers use oxy-fuel cutters to cut steel parts from the ship. As a first step, the big blocks are cut from the ship; then these blocks are transferred to the secondary cutting zone where they are cut further in order to meet the requirements of the scrap steel facility. Cut steel parts either stored in the ship recycling yard or transferred to rolling mills.

In the following sections, practices in Bangladesh, India and Pakistan will be presented in a detailed way. Overall ship processes have been analysed in detail for each country; system has been formulised to be the base for the modelling approach that is explained further in this chapter.

4.3.1.1 Bangladesh

Bangladesh uses the tidal beaching method which is much cheaper compared to the other methods. The simplified process model in Bangladesh is similar to Figure 4.11. The first step is the administrative step in which ship purchased is imported to Bangladesh. Then the imported ship is prepared for dismantling for the cutting processes in the primary and secondary cutting zones. After this step, hazardous materials are handled, and the usable material is segregated. The final step is the transfer of all the material from the yard to their final destination. The simplified process is given step by step in Figure 4.12 while the detailed flowchart can be found in Figure 4.13 (Colour codes of the process are identical with Figure 4.11).

Figure 4.12: Step by step ship recycling process in Bangladesh

Ship recycling process starts with the owner's decision to scrap and contacting potential buyers, usually through brokers. These brokers, also known as cash buyers, are usually in London, Dubai, Singapore and Hamburg (Hossain and Islam, 2006).

If the ship recycling yard wants to purchase the ship for recycling, first yard contacts with the cash buyers for the agreement. However, before buying the ship and importing the ship in Bangladesh, there are some steps to be taken as part of the Ship Breaking and Recycling Rules that came in effect in December 2011 (Shameem, 2012).

First, yard contacts the Ministry of Industries to obtain necessary approvals to import the ship. Before application, the conducting IHM survey is essential if IHM list does not exist. Memorandum of the Agreement of the ship's purchase, details of the ship and IHM of the ship is examined by the Ministry of Industries before issuing the '*No Object Certificate*' and '*Letter of Credit*' for the purchase of the vessel. More detail about this process can be found in the report of Ahammad and Sujauddin (2017) which was composed for the IMO's SENSREC project.

Once the letter of credit is issued by the Ministry, the ship can be purchased by the yard. Next step after the purchase is the bringing the ship to Bangladesh seas. On the last port, ship owner usually sells some of the consumables on board the ship (extra oil, paints, and so forth). Once the ship reaches Bangladesh seas, ship recycling yard notifies the Maritime Rescue Coordination Centre, coastguard, custom, Ship Building and Ship Recycling Board (Ministry of Industry), port authority, Department of Environment (Shameem, 2012, Ahammad and Sujauddin, 2017).

The necessary documents are submitted to these agencies to acquire beaching permission. Customs inspect the ships for contraband or illegal materials (Rummage Clearance Certificate). Also, Department of Environment, Department of Explosives and Fire, Ministry of Industry inspects the ship to ensure the overall safety of the dismantling of the ship. As soon as all the inspections and documents are completed, the ship is granted with beaching permission. While waiting for the beaching permission, ballast water in the ship is disposed of in the sea in the meantime.

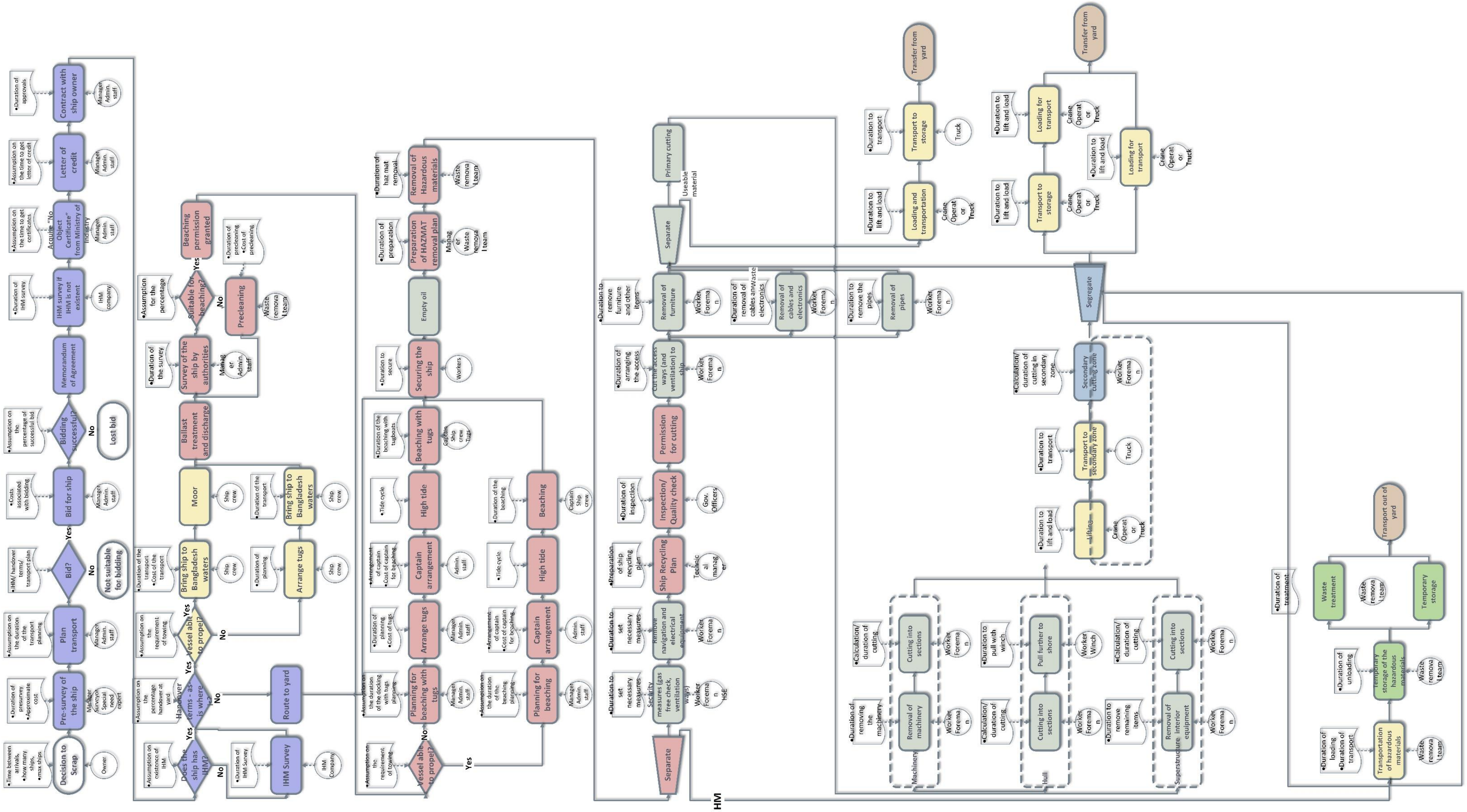


Figure 4.13: Step by step process flow for Bangladesh

As soon as the beaching permission is acquired, captain and other crew are prepared for the beaching step. Depending on the tide conditions, the ship is beached as soon as possible. After the beaching, the ship is secured in the beach (Figure 4.14). Also, the navigation equipment on board the ship is dismantled, and this equipment is taken by the Bangladesh Navy. Apart from the navigation equipment pyrotechnics such as distress signals is also handed over to the Bangladesh Navy (Shameem, 2012). Unused oil and fuel on board the ship are removed and sold to the dealers or factories, oily sludge and used oil is stored in the yard for separation later on and to be sold to brick firms and other consumables (chemicals, paints). After this step, yard receives the approval from Ministry of Industries for the permission of cutting. The yard submits the ship recycling plan along with other documents such as evidence of removal equipment and delivery of the navigation/radio equipment, a gas free certificate from DOE. Also, other wastes such as asbestos and glass wools are removed from the ship in this step. Safety checks and gas free operations are conducted before commencing the cutting.

After the safety check and cutting permit, workers go on board the ship and start cutting from the front of the ship and continue to the aft. Hundreds of workers are involved in this step (Most of these workers are temporary workers through a contractor). The procedure used in Bangladesh is heavily dependent on manual work and the most common method is cutting the pieces using oxy-fuel torches.

Figure 4.14: Ship in the primary cutting zone, propellers and side plates of the ship are removed (Chittagong – Bangladesh. October 2015)

Starting from the front of the ship, workers cut big blocks and drop in on the beach which is called the gravity method. Due to the OHS&E problems, this method is heavily criticised. These blocks are then pulled to the secondary cutting zone with the help of motorised pulley but also workers assist this part manually. Once these big “chunks” pulled further up the shore, workers also cut these blocks into smaller pieces so that they can be transferred with trucks. As the blocks are cut from the ship and transferred to the shore for further cutting process, the overall weight of the ship reduces as well. Reducing weight makes pulling the ship further to the shore during high tide easier Figure 4.15.

Figure 4.15: In the front, remaining block of the almost completed operation; in the background ship waiting for cutting permission (Chittagong – Bangladesh. October 2015)

Once these blocks are cut into smaller pieces, they are transferred to storage/segregation zone (Figure 4.16) for further segregation and separation with cranes or manually by the unskilled workers.

Figure 4.16: Segregation and store zones in a Bangladeshi Ship Recycling Yard (Chittagong – Bangladesh. October 2015)

Once the segregation is complete, these stored materials, parts or equipment are transferred to the steel mills, furnace or other buyers with trucks. Similar to the previous part, transfer to trucks is done by either crane or manually by workers. Also, other equipment, such as purifiers, pumps, motors, generators, etc. are carried to the storage with a crane if possible. Apart from these heavy parts and products, the rest of the materials are carried by the unskilled workers manually to the segregation or storage zone depending on the material. A ship contains so many different kinds of equipment. Some of these equipment are sold directly by ship recycling yards themselves. But sometimes some of the equipment is sold to an independent trader (e.g. accommodation, outfitting, engine, machineries, small pumps, generators, navigation tools, electrical and electronics goods, furniture's, kitchen utensils, sanitary items, accessories, cables and paints chemicals) through a spot tendering process (Shameem, 2012). Depending on the agreement and tender, sometimes these traders are also responsible for removing this equipment but sometimes yard removes and sells them later on. These traders sell these components in the second-hand shops in Chittagong. The duration of the above-mentioned process of ship recycling differs from ship to ship. According to Shameem (2012) the process takes 2-3 months depending on the type of ship, Hossain and Islam (2006) report that a typical cargo ship takes 5-6 months to dismantle.

4.3.1.2 India

Ship recycling procedure in India starts similar to Bangladesh: once the owner decides to scrap the ship, buyers are contacted, and the bidding process is done (Figure 4.17 and Figure 4.18). When the yard buys the ship, IHM survey is conducted if the ship does not have the IHM list. Once these steps are complete, end of life ship is prepared its journey to Bhavnagar where it will be anchored. In this preparation step, cargo spaces are cleaned, dried, gas freed and certified for gas-free procedure if the ship is Oil or Chemical Tankers, OBO, Gas Carrier.

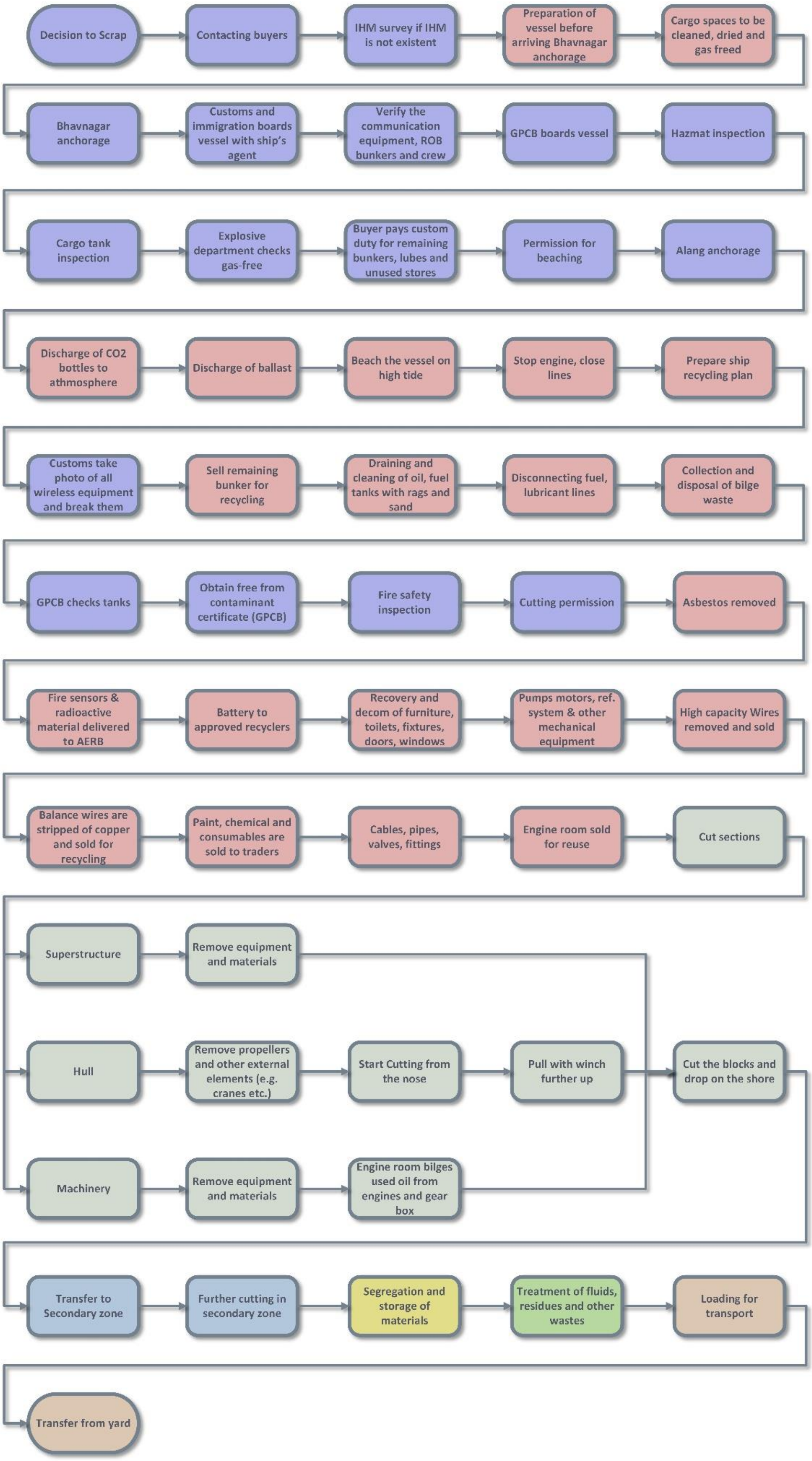


Figure 4.17: Step by step ship recycling process in India

After the cleaning and gas free process, the ship is taken to Bhavnagar anchorage. In Bhavnagar, Customs and Immigration boards and inspects the end of life ship's communication equipment, bunkers, crew list. Next, Gujarat Pollution Control Board (GPCB) boards the ship end inspects the cargo spaces, deck, accommodation and engine room for the hazardous materials and the cargo tanks for cleanliness (Sivaprasad, 2010). In addition, an inspector from the Explosive department conducts a gas free check. Following this step, the buyer of the ship needs to pay the customs duty for import related to the remaining consumables on board the ship (e.g. oil, lubes, fuel and so forth).

Once these steps above are completed, Customs and GPCB give the clearance to the beach the ship (ILPI, 2016). Next, the ship is taken to the anchorage of the yard (e.g. Alang anchorage). In the anchorage, CO_2 bottles are released to the atmosphere and excess ballast is released into the sea. Following the high tide, the ship is beached at full speed by a captain who is specialised in this operation.

When the ship is beached and secured safely, ship recycling plan is prepared by an expert in the yard using all the information provided by the owner including the drawings and logs. Also, ship recycling yard sells the extra fuel, oil and lubes remained on the ship after the beaching. Tanks are cleaned with rags and send after removal operation, and GPCB inspector checks the tanks and gives cutting permission if the conditions are satisfactory (Sivaprasad, 2010).

The important point with ship recycling process in India is that once the ship is beached, Customs once more boards the vessel to take photos of all the wireless communication equipment on board the ship, break each one, and take photos (JICO, 2017). This is done in order to prevent terrorist organisations to get a hold of this equipment.

Before starting the cutting procedure, ship recycling clears the hazardous material on board the ship. Using the IHM list, all previously identified Asbestos material is removed from the vessel and stored in the related storage. Apart from asbestos, other Glass wool and other insulation materials are also removed and transferred in storages. Fire sensors are the materials that potentially have radioactive material. Therefore, these and other equipment that might have radioactive materials are delivered to Atomic Energy Regulatory Board (JICO, 2017).

Apart from these, batteries are removed and given to approved recyclers, engine room bilges, used oil is collected and stored, high-quality cables are sold for reuse, and other cables are stripped for the core material (usually by burning). Furniture in the accommodation area, kitchen equipment and domestic consumables electronics are valuable items that can be sold in the second-hand market. Also, unspent paint, Chemical and consumable stores are Removed and sold to traders for resale.

Once these hazardous materials are removed, workers start cutting the ship as strips and using the gravity method, these strips “lands” on the ground. These blocks are transferred to secondary cutting zone (mainly using winches) for further dismantling and transferred to segregation zone or storage to be transferred to steel rolling mills.

Apart from the steel, stainless steel and other Non-ferrous material are segregated and sold for recycling. Also, all engine room and deck machinery are sold for reuse. Equipment that are not used for reuse are sold for melting.

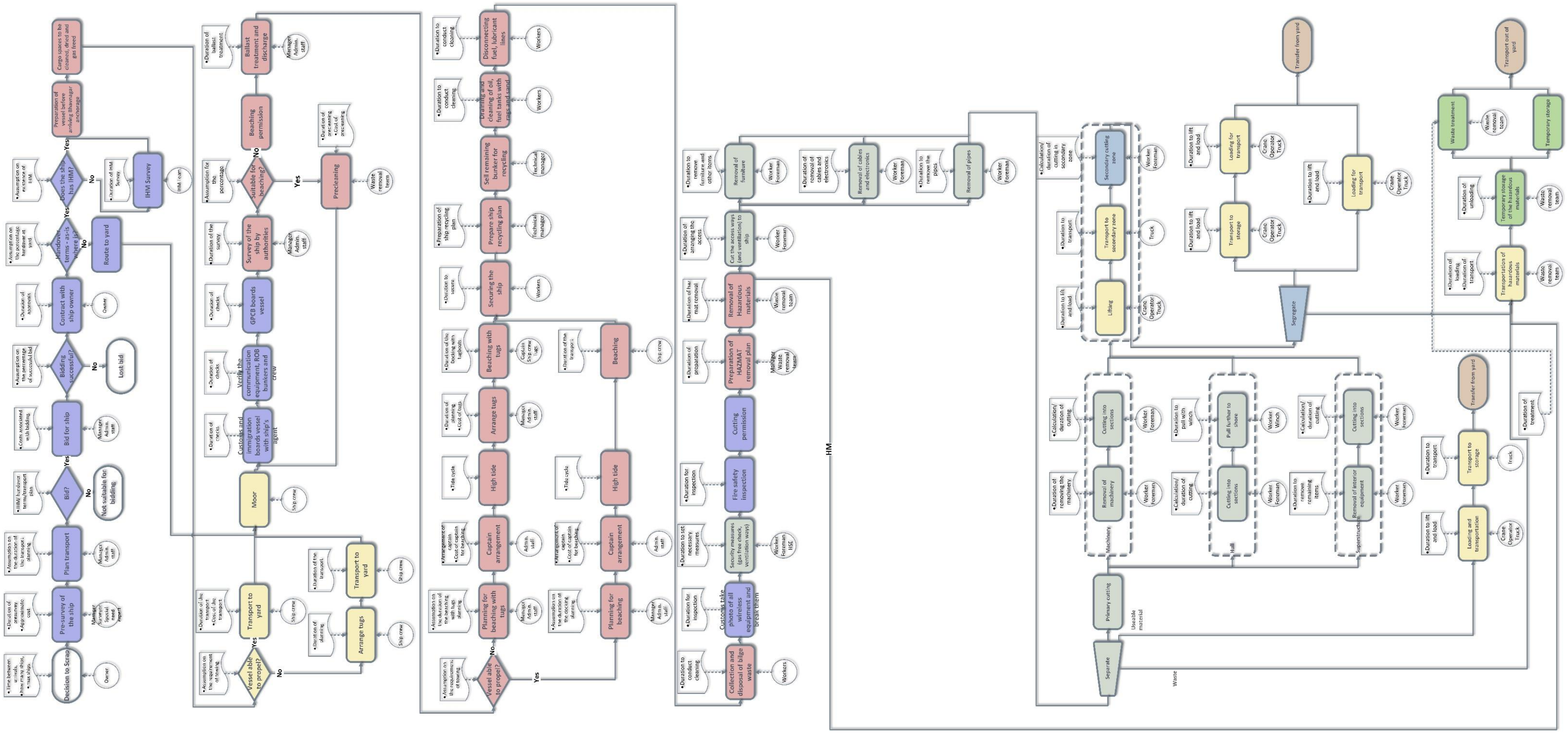


Figure 4.18: Step by step process flow for India

4.3.1.3 Pakistan

The beaching zone in the Pakistan yards is sandier compared to India and Bangladesh which allows better conditions and more mechanised operations. Furthermore, the difference on the tide levels is lower compared to Bangladesh, which makes the beaching process easier. Cranes can be used to transfer steel parts in the yards as well as to transfer to the trucks. Similar to Bangladesh and India, gravity method is used for the initial cutting of the blocks; the blocks are cut and dropped to the beach or sea depending on the tide conditions (NGO Ship Breaking Platform, 2014b).

Similar to Bangladesh and India, most of the operation is conducted on the beach with no impermeable floor. Therefore, all the toxic wastes including the spills and liquids contaminated the beach and water with the effect of the tide. Also, currently there is no waste treatment facility in Gadani area. Therefore the fate of the toxic wastes are unknown. Similar to India and Bangladesh, soil, water and air around the yards are incredibly polluted. For example, fishing activities came to a halt due to the pollution (ILPI, 2016).

Similar to Bangladesh and India, once the owner decides to scrap the ship, buyers are contacted, and the bidding process is done (Figure 4.19 and Figure 4.20). When the yard buys the ship, BEPA (Environmental Protection Agency, Balochistan) makes the initial environmental examination and environmental impact assessment (DIVEST, 2009a). If BEPA has no objection, issues the '*no objection certificate'* to the yard and gives clearance to import the ship. After these approval steps, contract of the ship is completed, the ship is brought to Gadani and beached on the shore. Following the beaching, the ship is secured, and access to ship is arranged. All loose items are removed from the ship.

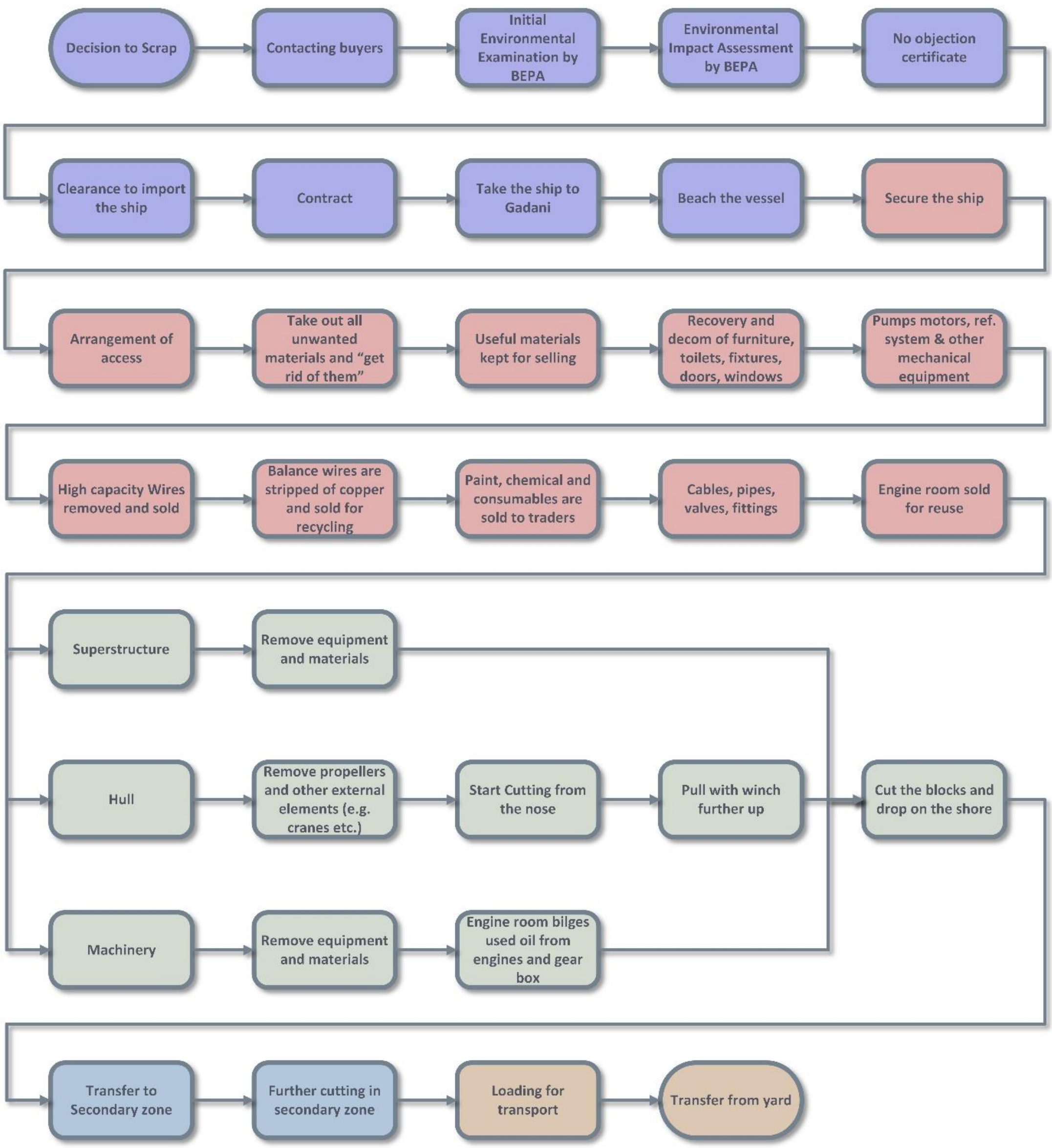


Figure 4.19: Step by step ship recycling process in Pakistan

Hazardous and non-valuable items are disposed of (Currently the faith of these materials are not evident), and useful materials (furniture, toilets, fixtures, pumps, motors, wires, remaining consumables) are stored for selling or sold directly to the traders. In parallel to the removal, structure of the ship is also cut, transferred to the shore and cut further into the smaller pieces similar to other countries. These smaller parts are loaded on the trucks and moved to the steel mills.

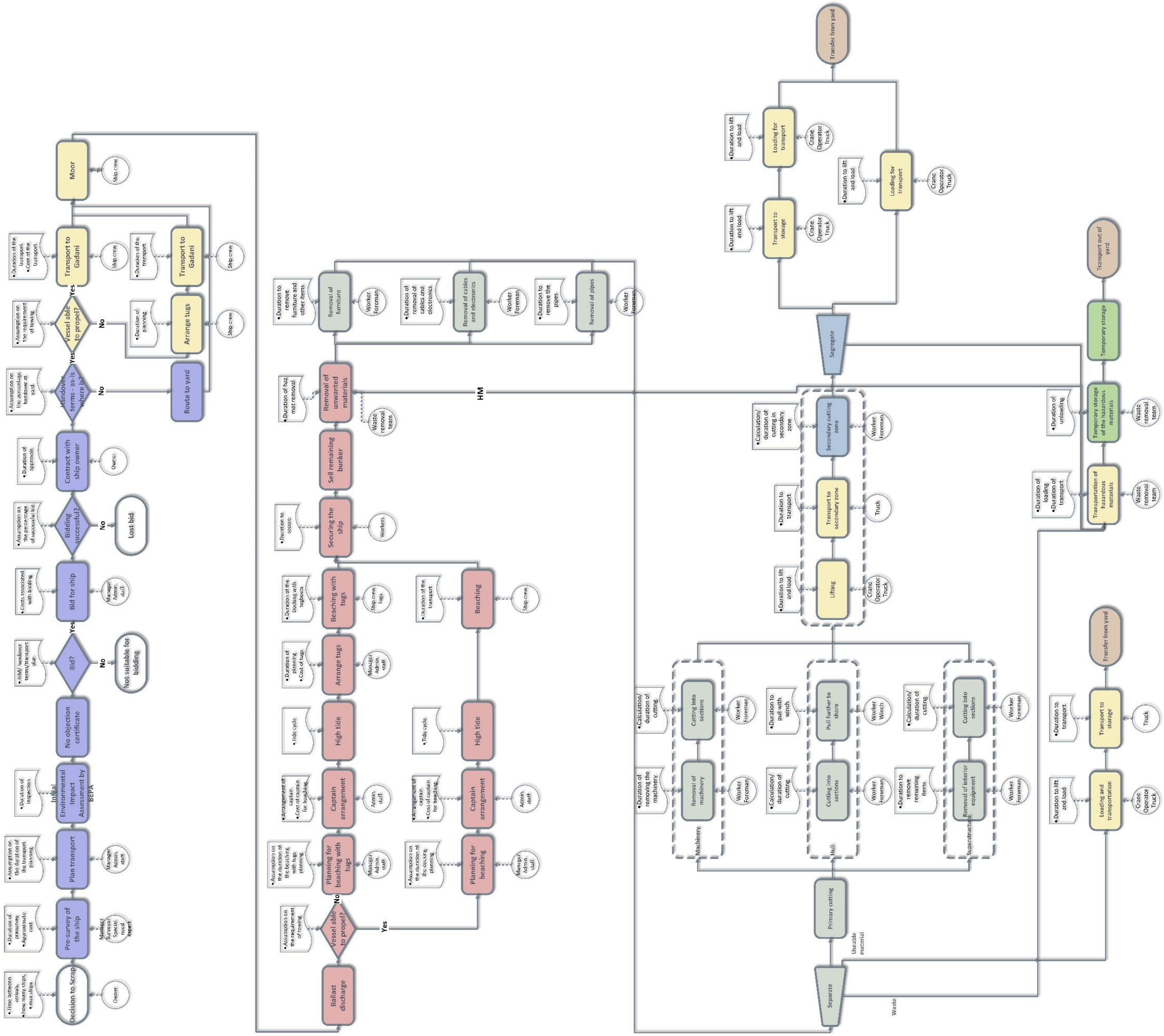


Figure 4.20: Step by step process flow for Pakistan

4.3.2 Slipway

Slipway (also known as landing) is similar to the beaching. However, in the slipway method, the floor is the impermeable (concrete), and the lack of tide makes it easier to manage the wastewater and other liquids. Therefore, this method is considered more environment friendly than beaching. Slipway method is applied in several countries but Turkey has the highest capacity amongst these countries. Therefore, Turkey's method of ship recycling will be investigated in this chapter.

Figure 4.21: Ship recycling operation in a typical Turkish ship recycling yard.

All the yards in Turkey are using the slipway method. The ship is landed on concrete slipway with its own power and pulled up the shore on concrete surface gradually as they start cutting the steel block from the front of the ship. The operation is mainly mechanised compared to India, Bangladesh and Pakistan. The ground is mainly concrete, and oil booms are used commonly to prevent pollution and spillage into the sea. Due to the solid concrete floors, use of cranes are possible in the yards. Also, trucks can drive close to the ship, and the cut pieces can be loaded onto trucks by the cranes. Overall diagram for ship recycling operation in a typical Turkish ship recycling yard is given in Figure 4.21 and detailed diagram is given in Figure 4.22. Once the contract for the end-of-life ship has been made, the ship arrives in Anchorage to Aliaga, Izmir (depending on the delivery terms). After the arrival, initial check on the ship for fuel is conducted by Customs, Maritime Police and port authority (Gemisander, 2017). As a result of this check, docking (or beaching) permission is given and depending on the ship's condition; ship is docked to the slipway with its power or towed with a tugboat. The ship is secured with chains, oil booms (for spillage containment) and other measures following the docking process. As a next step, waste management centre team of Shipbreakers Association of Turkey check the ship for radiation and gas (Gemisander, 2017). If the ship is free of gas and radiation, harbour and customs board the ship for the fuel and sludge survey. The ship is disinfected for vermin and bugs if necessary after the previous step; port authority also identifies complementary goods on board the ship. The provincial department of environment confirms the IHM list of Waste Treatment Centre, develops the IHM report and if everything is in order confirms the notification. Following the notification, the customs office gives the clearance to import, and after the import steps, port authority gives the dismantling clearance. After getting the clearance of dismantling, Waste Treatment Centre first removes the waste that is accessible easily from the ship and then removes the asbestos and other hazardous materials from the ship (ShipDIGEST, 2013). After the waste removal safety checks, gas free and organisation of ventilation is done, and ship recycling plan is prepared.

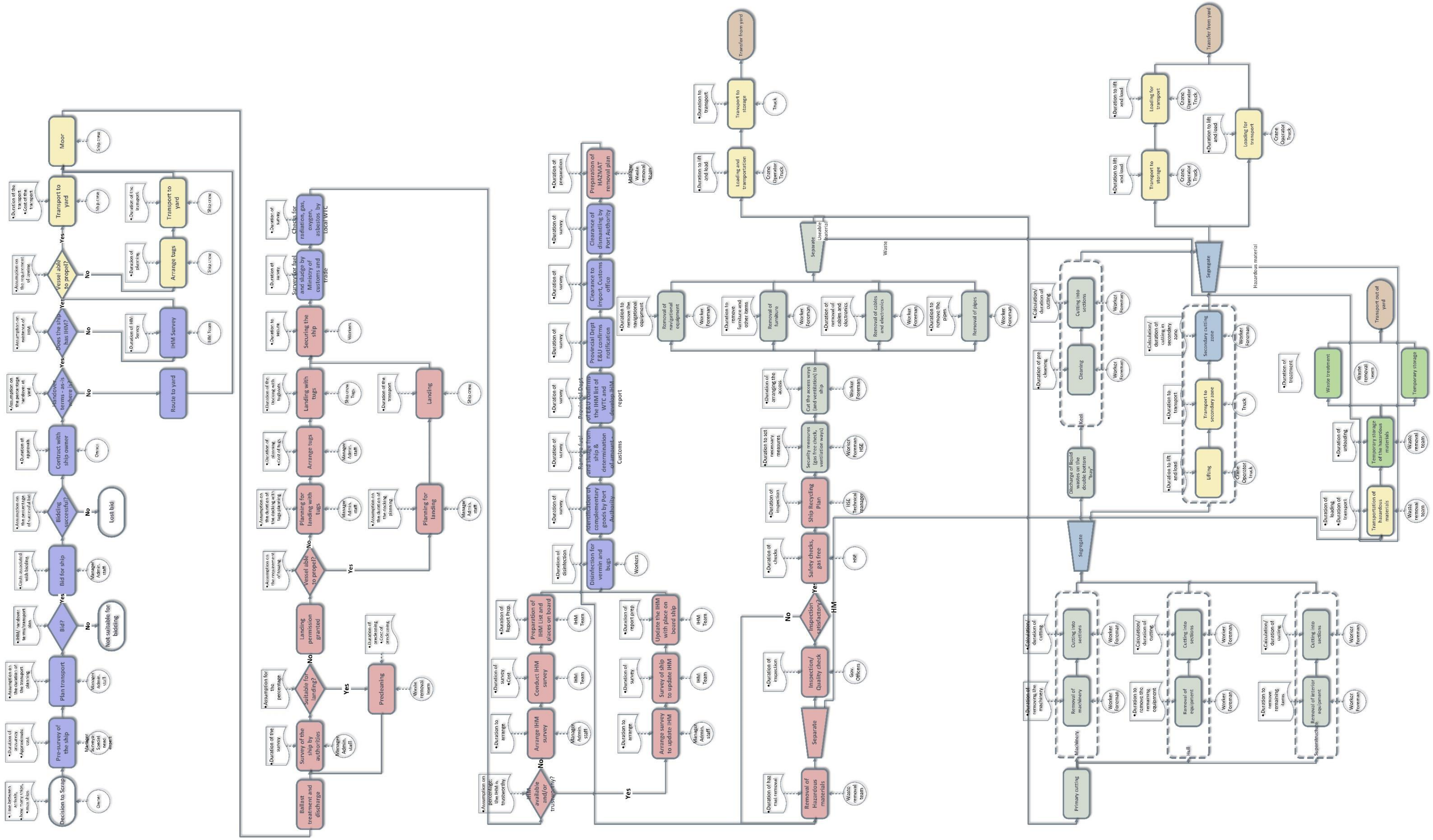


Figure 4.22: Step by step process flow for Turkey (Slipway)

Operation starts from the fore of the ship and continues through upper decks. Dismantling operation is done from upper decks to lower decks all the way to the engine room, leaving the hull plate, or also known as a tray, untouched. This is done to maintain the stability of the ship as well as to collect the liquid wastes in the double bottom of the ship. Once all the parts inside the hull, including all the equipment and machinery, the “tray” is pulled up onto the land where it is dried up with pumps and completely dismantled (DIVEST, 2009a).

4.3.3 Quayside

In the quayside method (also known as pier breaking, alongside or top-down (ILPI, 2016), the ship is berthed alongside a pier and then dismantling process starts from the top deck down to the bottom of the ship. Even though there is a risk of spillage during dismantling, the risk is lower compared to the beaching method. Alongside is mainly used in China and some European ship recycling yards (e.g. Spain, Belgium, The Netherlands, Great-Britain, Italy, Lithuania (European Commission, 2016)). Chinese method of quayside will be investigated in this section.

The quayside method eliminates the beaching step from the dismantling operation. Ships are dismantled top-to-down approach while they are still in the water. Environmental pollution control in this method is better than the beaching method as the Chinese yards use oil booms and other measures to prevent the pollution of the sea. The overall process of ship recycling yards (that are using the quayside method) will be summarised in the next section.

Once the ship arrives the Chinese waters, experts boards the ship, examine the conditions, collect data and develop dismantling strategy (Figure 4.23 and Figure 4.24). Then access ways to the shops are set, and passageways are opened. For the health and safety, signs are placed where necessary hatches for ventilation are opened, gas-free operation is conducted, and other measures such as spill containment booms are placed. Once all the measures are in place, and ship recycling plan is prepared, all the loose items as well as the waste including the hazardous waste are removed from the ship. After this step, the cutting operation starts.

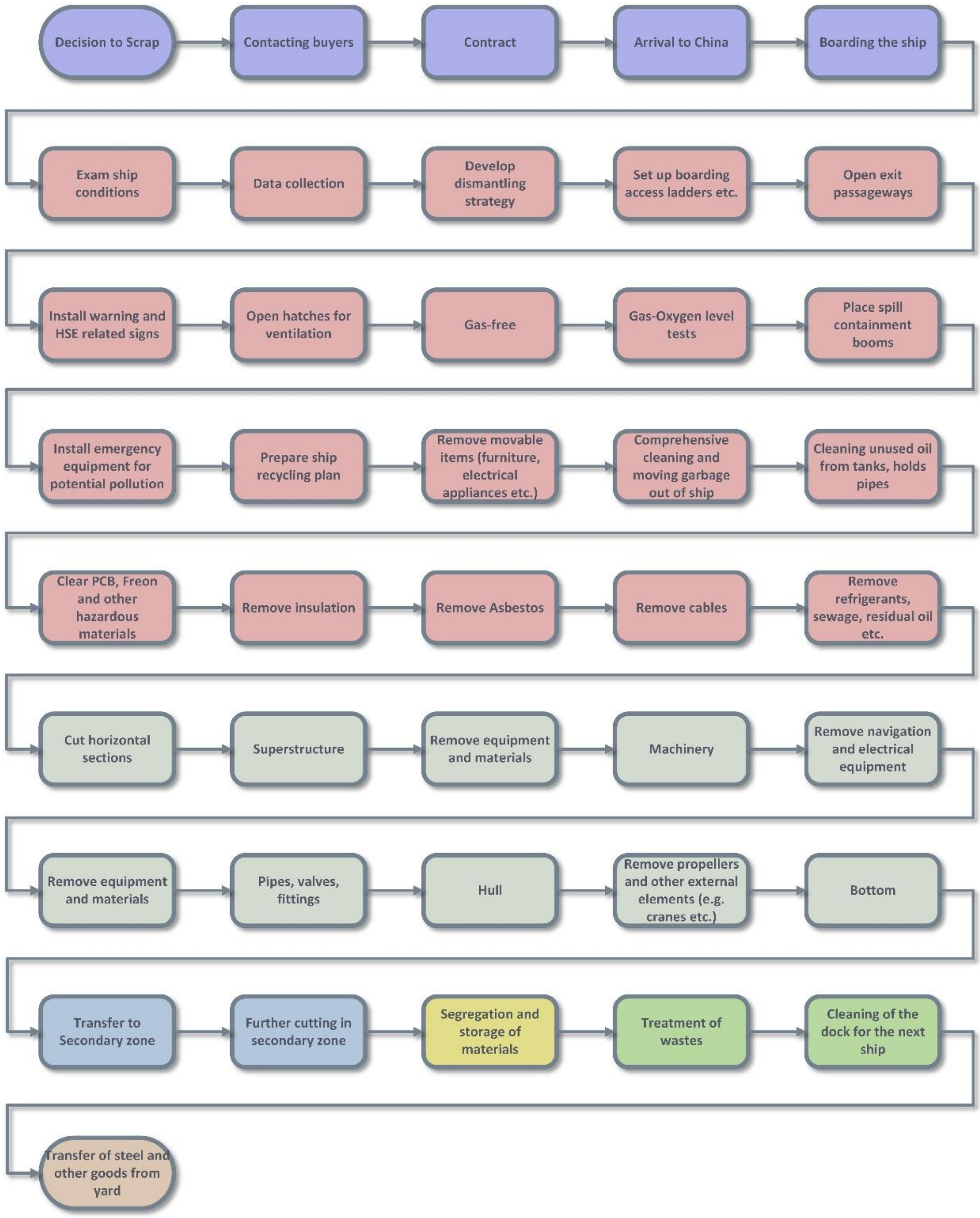


Figure 4.23: Ship recycling process in Chinese yards

Cutting operation follows the welding lines and during dismantling the superstructure and deck, top to down and outside to inside approach is followed (Du et al., 2017). During this process, any fixed equipment and material encountered is also removed. Hull cutting, the process is conducted with the order of forward, aft, then the middle. During this stage, it is essential to keep the balance to avoid sinking. The remaining bottom of the ship is transferred to the shore and cut into further pieces. Similar to the other methods, segregation, storage and transfer of the materials are conducted.

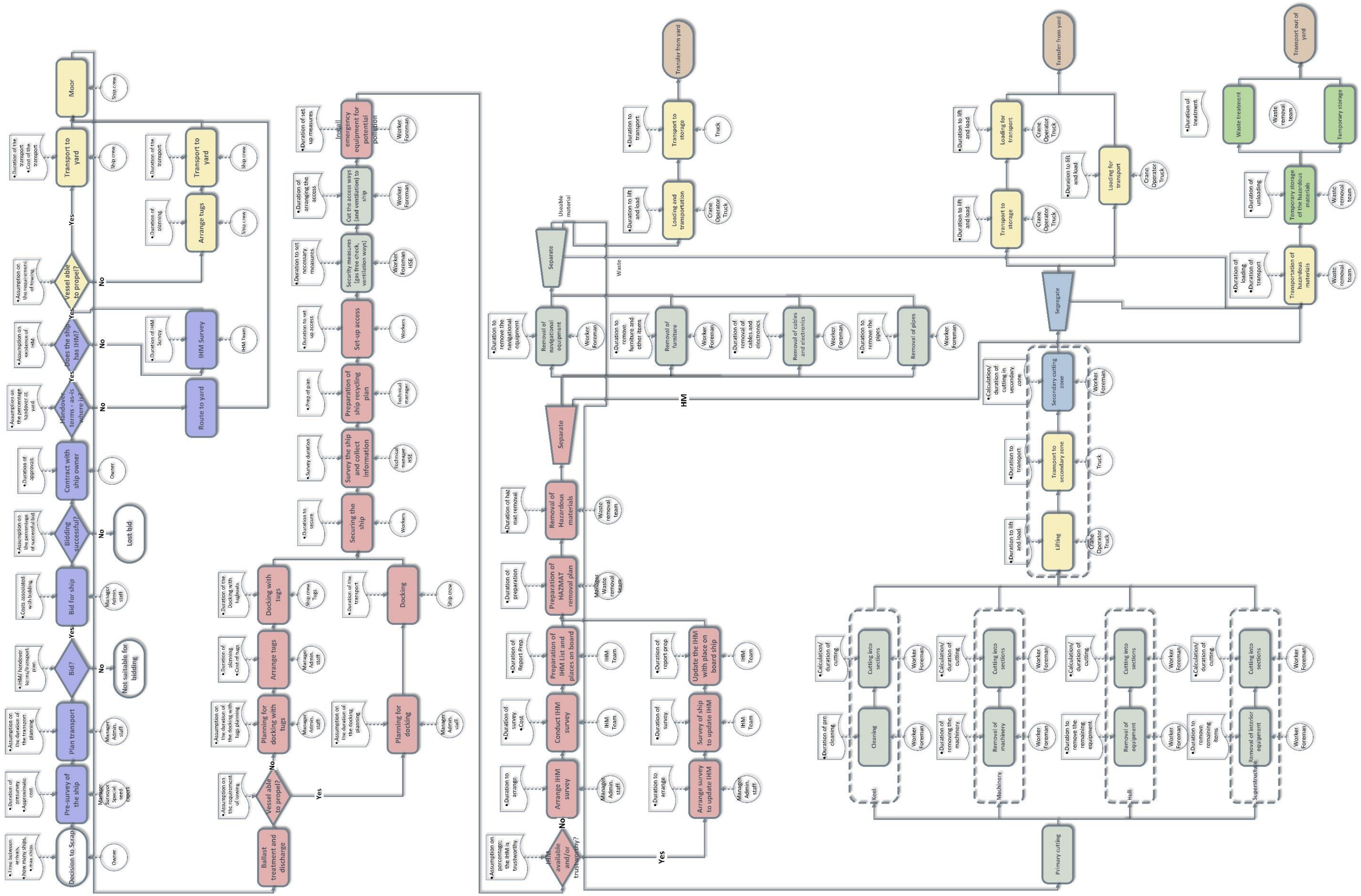


Figure 4.24: Step by step process flow for China (Quayside)

4.3.4 Dry-Dock

Dry-dock approach is often referred as the safest method for environment compared to other methods as the dismantling process is done in a contained area the risk of spillage to the sea is lower (ILPI, 2016). Once the ship arrives ship is placed in dry-dock, the water in the dry-dock is emptied, and the dry-dock is cleaned before filling with water again after the ship is dismantled. Dry-dock method is mostly applied in some European Countries (yards from France, Latvia, Netherlands, Portugal, United Kingdom are listed in the European ship recyclers list (European Commission, 2016)), some yards in China, US and Canada.

Even though the capacity in these countries is in place, dry-dock is more expensive compared to current methods in South Asia. Also, the costs related to health, safety and environment-related measures, these yards are not able to offer high steel price for per tonne. The profit is also low, but since China is planning to ban the export of end-of-life ships and none of the Turkish yards is in the European Ship Recycler's list, there is an opportunity for these yards if they can target the responsible ship recyclers.

Since the application of the drydock is limited and the application method is very similar, a generic process model for the method is given here, rather than a country-specific approach in the previous sections. In the preparation of this generic process model UK (DIVEST, 2009a) and US (OSHA, 2010) ship recycling methods are investigated and combined.

Similar to the other methods, the first step of the ship is the initial visit to the ship is organised. The main aim of this survey is to check the hazardous materials and the ship's overall condition (seaworthy, self-propelled). Using the information collected from this initial survey, hazardous material sampling and removal plan, as well as the transport plan, are prepared. Depending on the ship's condition, the ship is towed, or self-propelled to the yard and the mooring operation is conducted. Mooring is a critical step of the dry-dock operation; it should be planned as the bad weather can adversely impact (delays, accidents, and so forth) the mooring operation. Once the ship is safely moored and secured with mooring lines, spill-containment booms are placed around the water to prevent environmental damage in case of a spill or accident.

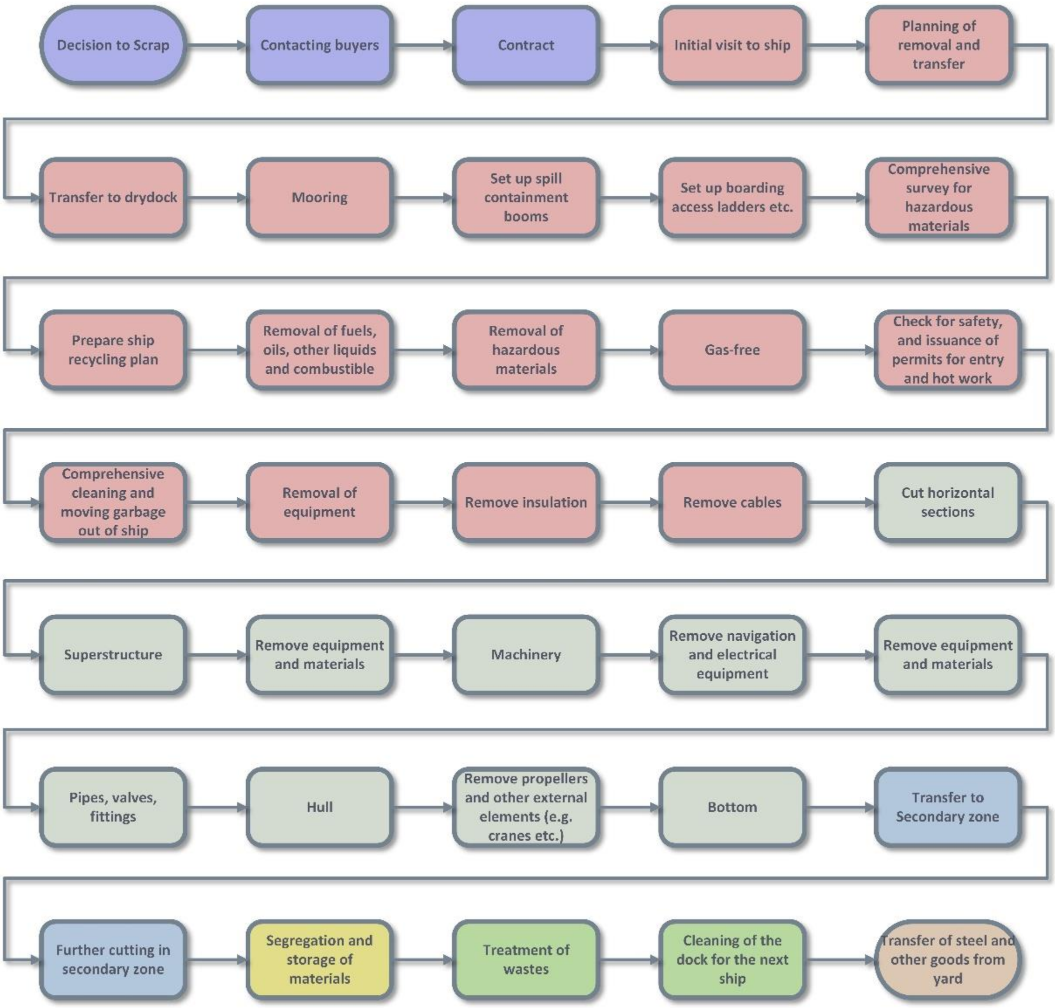


Figure 4.25: Dry-dock recycling process flow

During emptying the water in the dock, calculations for the stability and strength of the ship must be carefully conducted. After the mooring, comprehensive survey for the hazardous materials, including the PCB, asbestos, fuels oils, other liquids and combustible materials. These materials are removed first and treated by the relevant expert. As a next step, the ship is checked for entry, and hot work after the gas-free operation is also conducted. Once the approval for the work is acquired, equipment starting from fixtures, anchors, chains and small equipment are removed. Bigger equipment and machinery are removed once they are accessed, and there is a free path to remove them. Similar to the quayside, cutting operation starts from the aft and front of the ship from top to down and proceeds to the centre of the ship. Cut blocks are transferred to the secondary zone for further dismantling, segregation and transfer to the mills. In the dry dock method, mobile hydraulic shear cutters are also used commonly in parallel to this cutting operation. The flow of this model is shown in Figure 4.25.

4.4 Development of Generalised Ship Recycling Process Flow and Simulation Model

Different ship recycling approaches are being applied in different countries. The process flows are generated in this section to be converted directly to the discrete event simulation model. However, the current version of the process flows are too detailed and includes steps that will not affect the ship recycling yard's performance. For example, getting a recycling permit for the ship is related to an external body and also happens before the ship's arrival, therefore, it would not affect the performance of the yard. Therefore, for the simplicity and accuracy in the modelling, current ship recycling process flows should be simplified.

4.4.1 Simplification of the developed ship recycling processes

First step of this simplification, analysed ship recycling methods are reduced to one generic model per method rather than a country-specific model. The details of the administrative step, such as permissions from ministries, getting a no-object certificate from related bodies or the bidding steps, were removed from the model and changed with generic administrative steps or details of the hazardous material removal was combined as a Hazmat treatment, which are common for all the methods. Some of the processes involved in the recycling procedure are country-specific, however, these additional steps are included in the generic flow as the modeller can decide which ones to include in the process model. Also, the order of some of the process also changes from country to country, but modeller can decide the correct order, therefore, the simplified model represents the typical order of the procedure (Figure 4.26).

Steps shown in the process flow in Figure 4.26 can be designed separately for the countries involved if required as sub-models. Same colour coding in Figure 4.11 has been used in the generalised recycling models below.

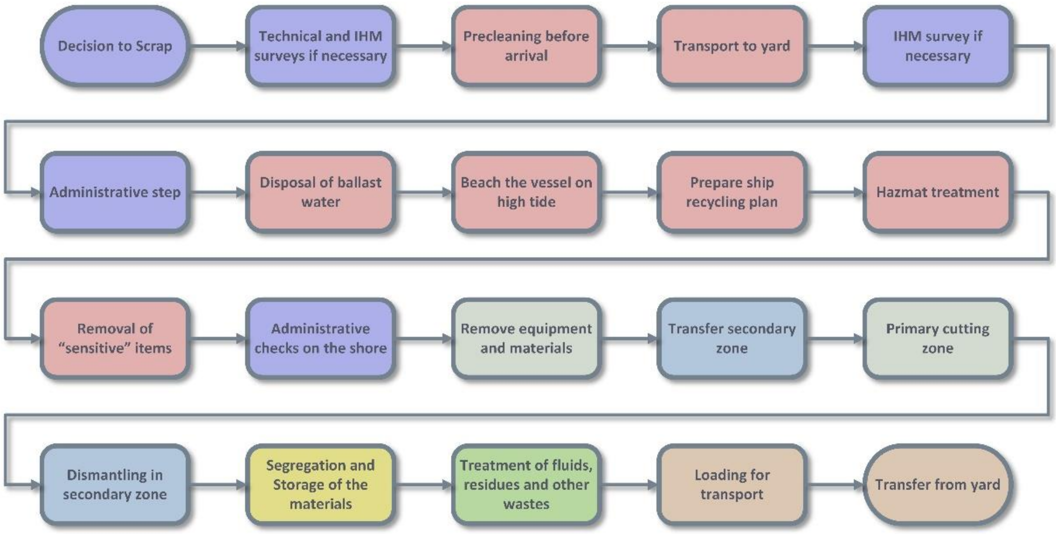


Figure 4.26: Simplified generic beaching process flow

Similarly, slipway, quayside, and dry-dock flows are also simplified by combining similar steps. These diagrams can be seen in Figure 4.27, Figure 4.28 and Figure 4.29.

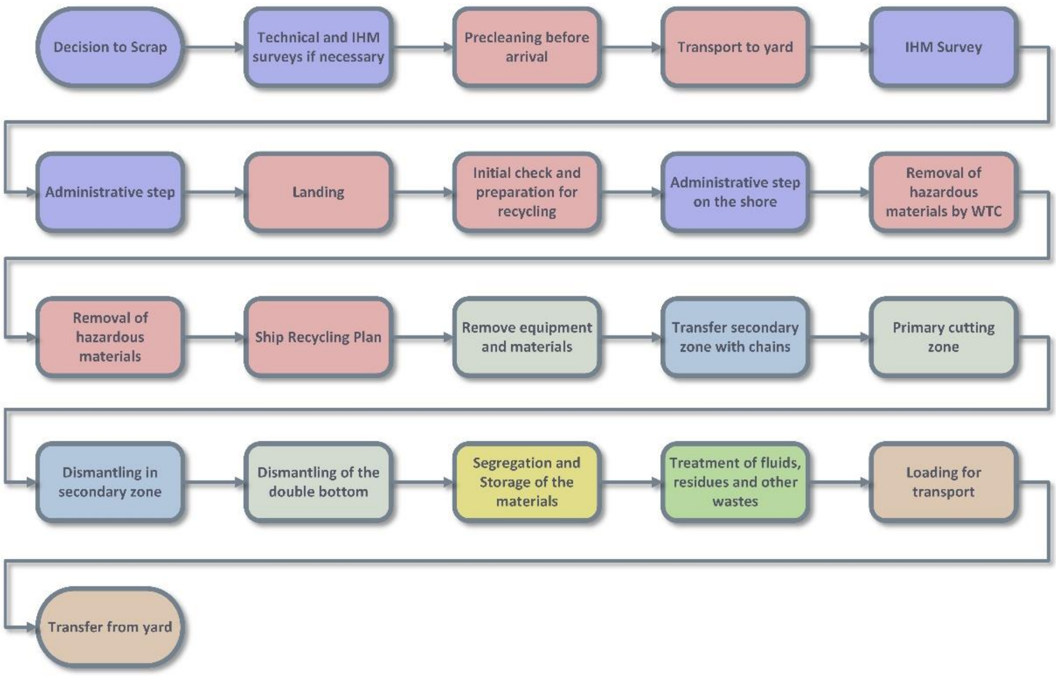


Figure 4.27: Slipway simplified process flow

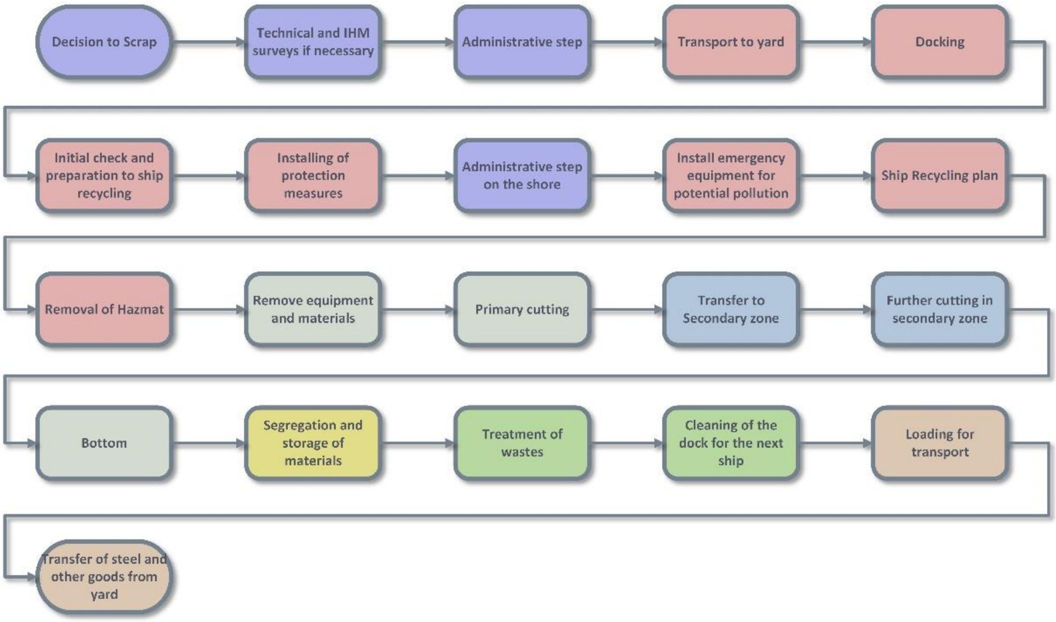


Figure 4.28: Quayside simplified process flow

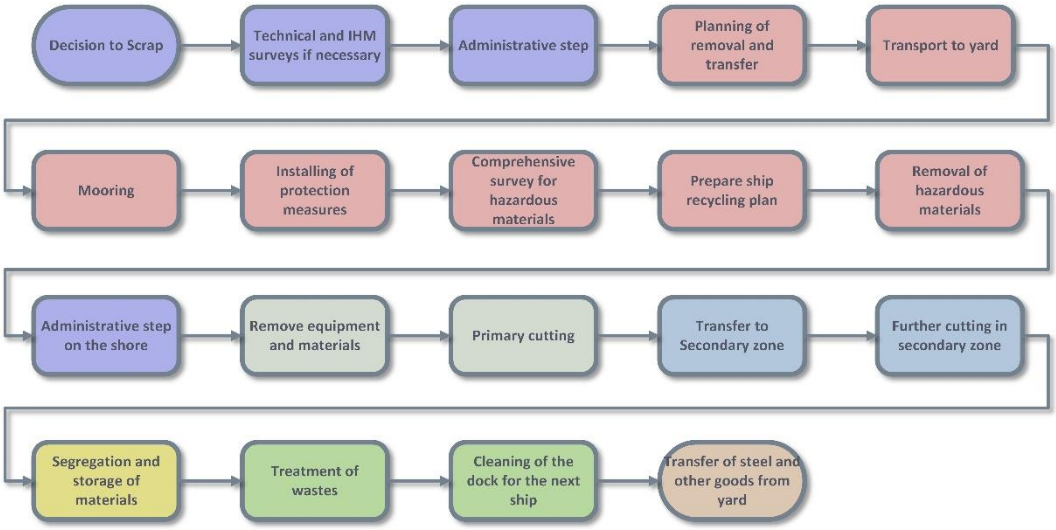


Figure 4.29: Dry-dock simplified process flow

Following the simplification process, ship recycling processes for these four different approaches were compared to generate a single ship recycling process flow.

4.4.2 Comparison of the Ship Recycling Methods

In this section, ship recycling methods are compared to generate a single ship recycling flowchart. Table 4.2 compares the ship recycling process flows of beaching, slipway, quayside, and dry-docking methods.

Table 4.2: Comparison of the ship recycling approaches

STEPS	Beaching	Slipway	Quayside	Drydock
Decision to scrap	•	•	•	•
Technical and IHM surveys if necessary	•	•	•	•
Precleaning before arrival	•	•		
Administrative step	•	•	•	•
Transport to yard	•	•	•	•
Planning of removal and transfer				•
IHM survey	•	•	•	•
Docking		•	•	
Mooring				•
Disposal of ballast water	•			
Initial check and preparation to ship recycling		•	•	
Installing of protection measures			•	•
Beach the vessel at high tide	•			
Comprehensive survey for hazardous materials				•
Prepare ship recycling plan	•	•	•	•
Administrative step on the shore		•	•	•
Removal of hazardous materials and wastes	•	•	•	•

STEPS	Beaching	Slipway	Quayside	Drydock
Install emergency equipment for potential pollution			•	
Removal of sensitive items	•			
Administrative checks on the shore	•			
Remove equipment and materials	•	•	•	•
Primary cutting zone	•	•	•	•
Transfer secondary zone	•	•	•	•
Dismantling in secondary zone	•	•	•	•
Segregation and storage of the materials	•	•	•	•
Dismantling of the double bottom		•	•	
Treatment of fluids, Residues and other wastes	•	•	•	•
Cleaning of the dock for the next ship			•	•
Loading for transport	•	•	•	•
Transfer from yard	•	•	•	•

Table 4.2 demonstrates that the processes followed in the investigated procedures are similar; there are only minor differences in the order of the processes and additional steps (e.g. dismantling of double bottom). Therefore, it was decided to generate a one generic ship recycling model to simplify the approach during the modelling. Differences in the modelling can be addressed by changing the order, adding necessary steps when necessary. In addition, ship recycling steps in these simplified diagrams are connected in series, however, in real life, some of these processes can be in parallel. This was also modified in the generic model to represent the flow in the ship recycling yards more accurately. All steps shown in the simplified process model (Figure 4.30)

can be designed as separate models with different options to represent the operation correctly, as well as to give the modeller required flexibility.

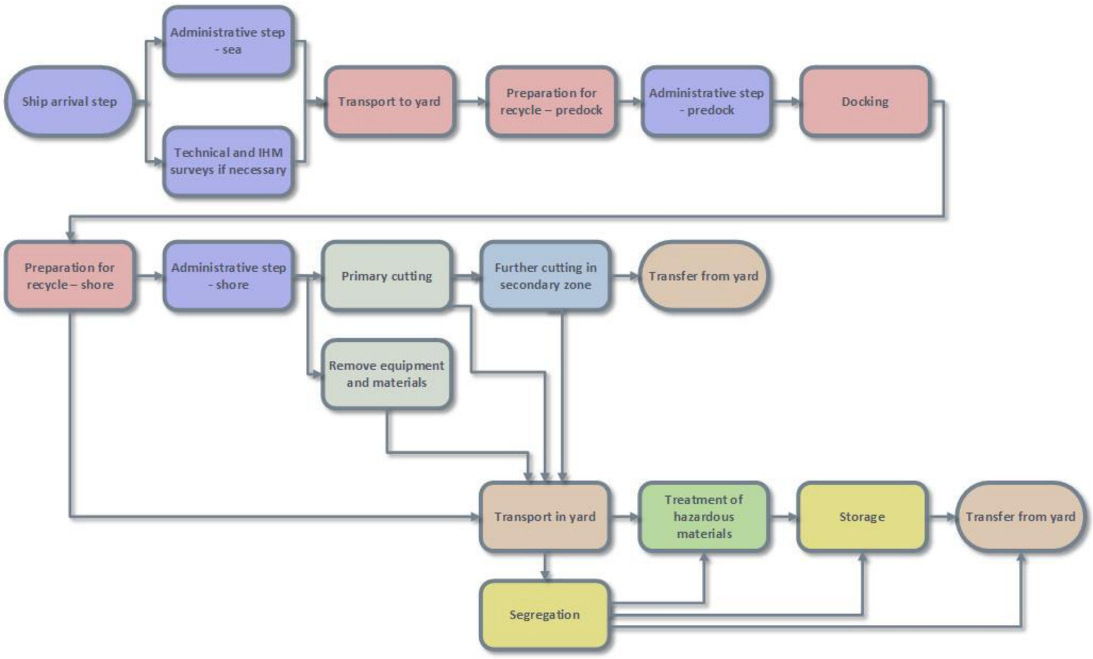


Figure 4.30: Simplified generic ship recycling procedure

All the elements in this representation can be designed as subprocesses, which are explained later in this chapter along with the data need and resources involved for each step. Resources associated with the process is given below the module, and the data needed is given above the module in the graphical representation.

4.5 Simulation Model for Ship Recycling Yard Operations Using Arena

The development of the ship recycling yard flow was a time-consuming process that required extensive study of the procedures, organisation of field studies and consultations with the stakeholders. This process flow will be utilised to develop the models in simulation environment.

This section describes the development of a simulation model of a ship recycling system based on a generic ship recycling process model developed in this chapter. These concept models offers high level customisation to the users and can be amended and adapted for any ship recycling method in any detail. Concept models given in this next section can be used or removed from the model depending on the steps to process or the level of detail of the model. The representation of this flow process in the Arena environment is shown in Figure 4.31. In order to simplify, the processes are shown as sub-models in the below figure. Each module within these sub-models will be explained in the following sections. Details of these models including the data needs to be collected to successfully run this model, resources involved with the given processes and the detailed Arena properties are given in Appendix C.

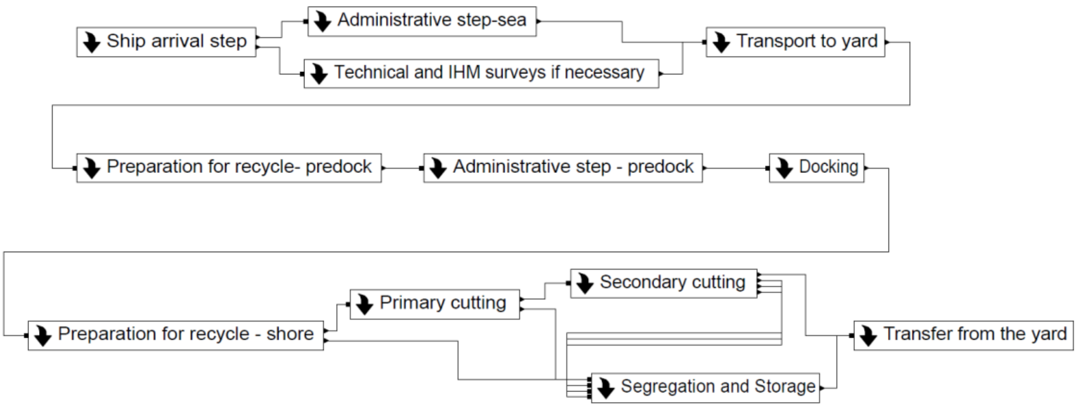


Figure 4.31: Arena representation of the simplified flow process using the sub-model logic

4.5.1 Ship Arrival Model

Ship arrival model represents the introduction of the ship to the system. In this step, ships that will be processed enters the ship recycling system to be processed further. Model representation and arena model of this step are given in Figure 4.32.

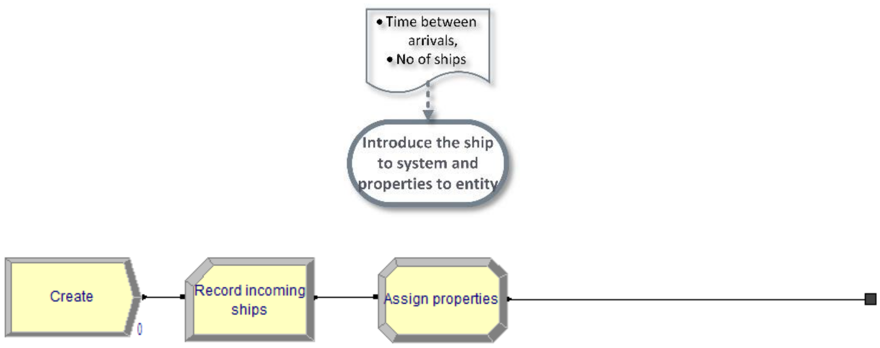


Figure 4.32: Ship arrival step graphical representation (above) and model in the Arena environment (below)

4.5.2 Administrative Model – Sea

This model represents the administrative duties before purchasing the ship and includes the step for information collection about the ship, taking approvals, bidding and contract (Figure 4.33).

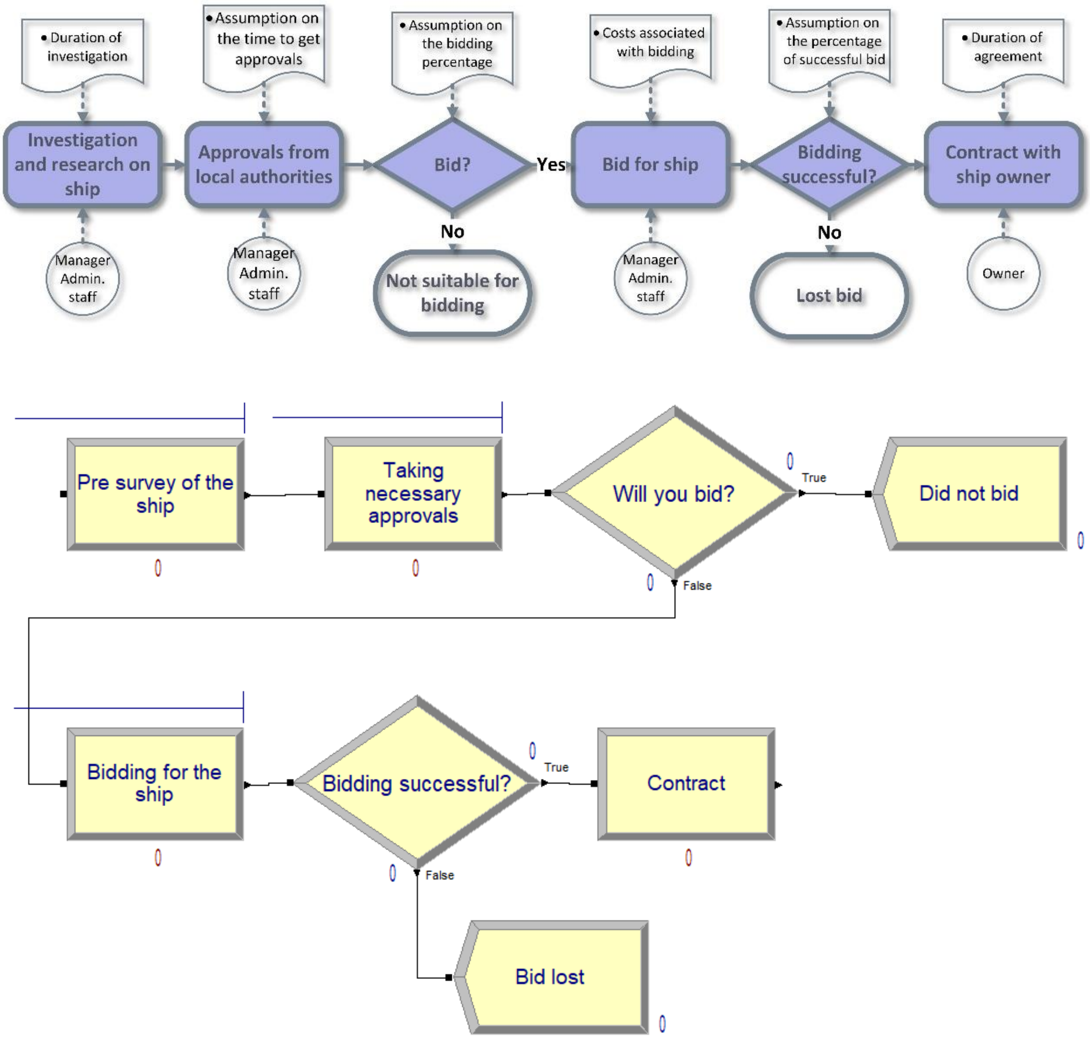


Figure 4.33: Representation of the administrative step at the sea.

4.5.3 Model for Technical and IHM Surveys

This model includes the technical and IHM surveys (if necessary) to be conducted before the ship's arrival. In this step, ship is surveyed to prepare the recycling plan, to plan ship's arrival and to prepare detailed inventory. Depending on the ship, IHM survey might be necessary before the ships arrival, which should be decided and conducted if necessary at this stage. Steps of this phase is given in Figure 4.34.

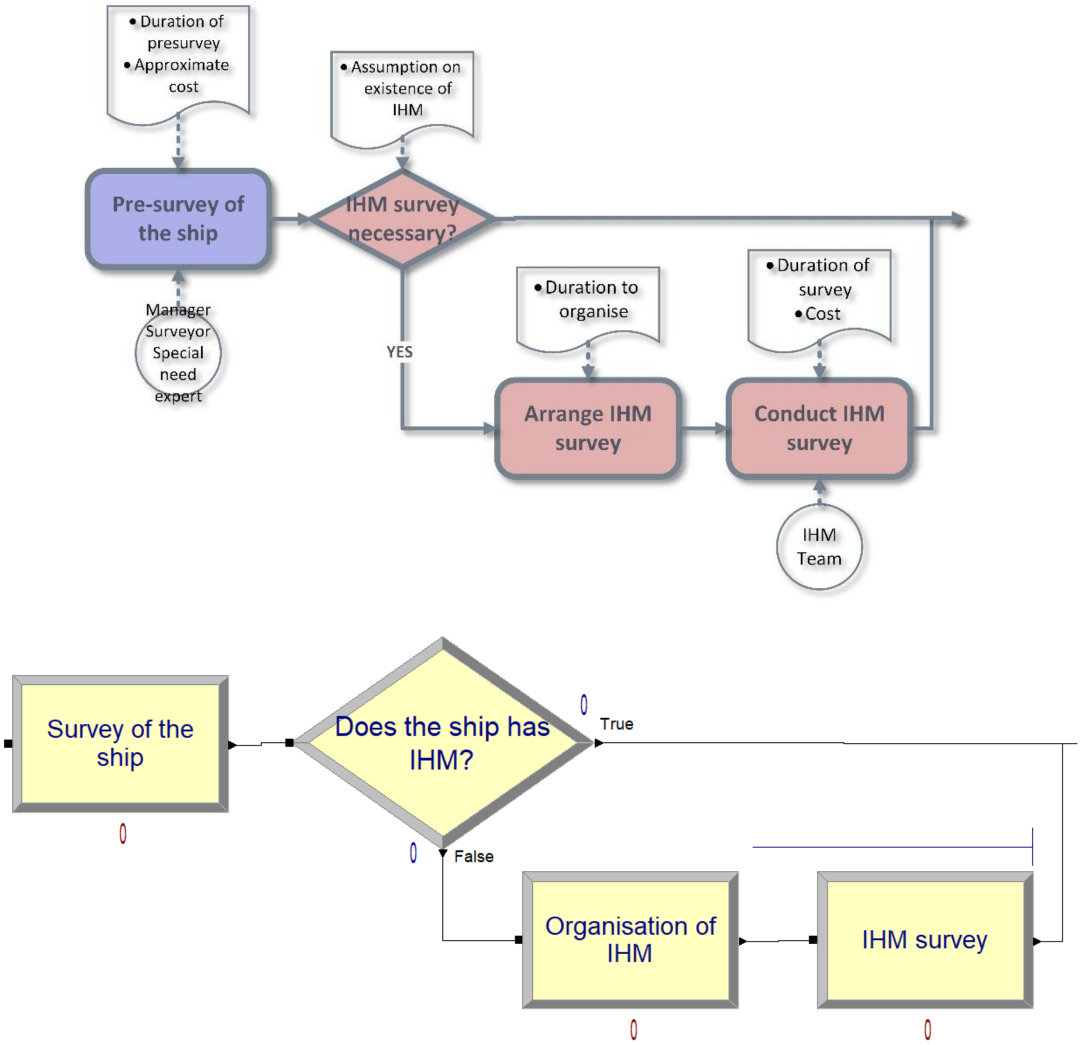


Figure 4.34: Survey model graphical representation (above) and model in the Arena environment (below).

4.5.4 Model for Transportation to Yard

This model represents the organisation of the transport to yard and the transportation of the ship to the yard. Depending on the condition of the end of life ship, this model includes tugboats for transferring the ship. Process flow of the model and the representation in the Arena environment is given in Figure 4.35.

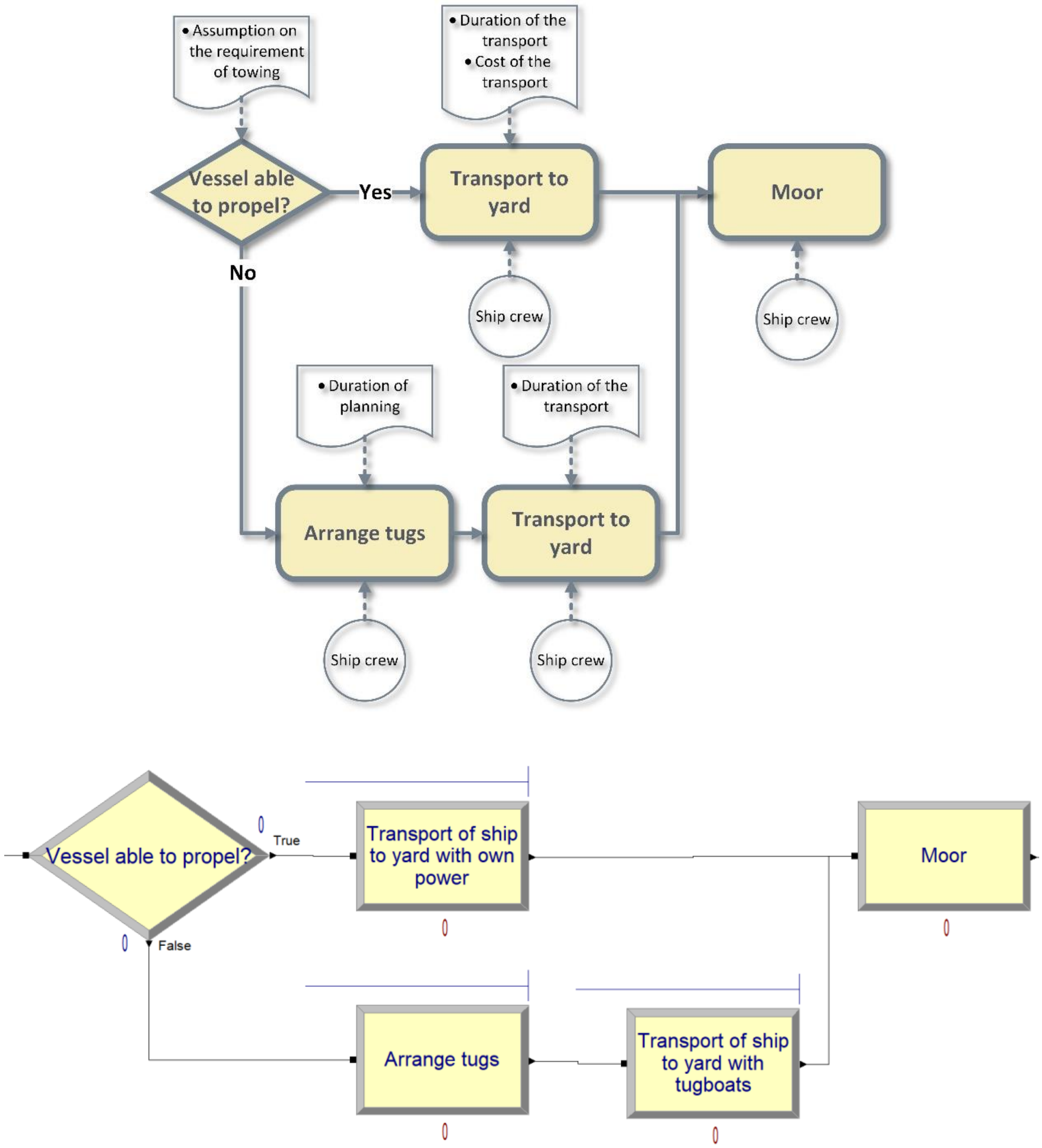


Figure 4.35: Transport Model graphical representation (above) and translated model in the Arena environment (below)

4.5.5 Preparation for recycling - Predock

This model focuses on the preparation that needs to be done on the ship (while it is moored close to the yard) before docking. In this step, ballast water on board the ship is treated (or discharged), and general cleaning can be conducted.

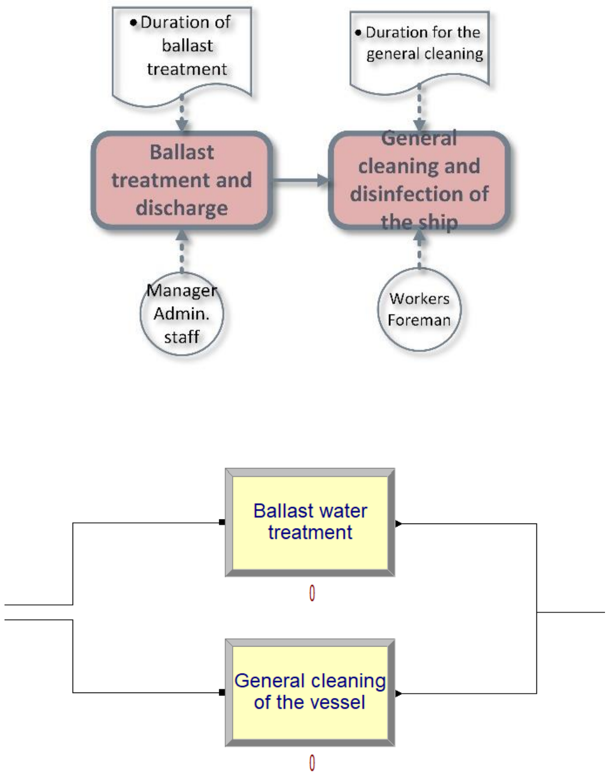


Figure 4.36: Preparation to ship recycling - predock (above) and translated model in the Arena environment (below)

4.5.6 Administrative Step - Predock

In this model, the legal approval process prior to docking operation is conducted. Following the application and survey, docking permission is granted according to the ship’s condition. Representation of this model is shown in Figure 4.37.

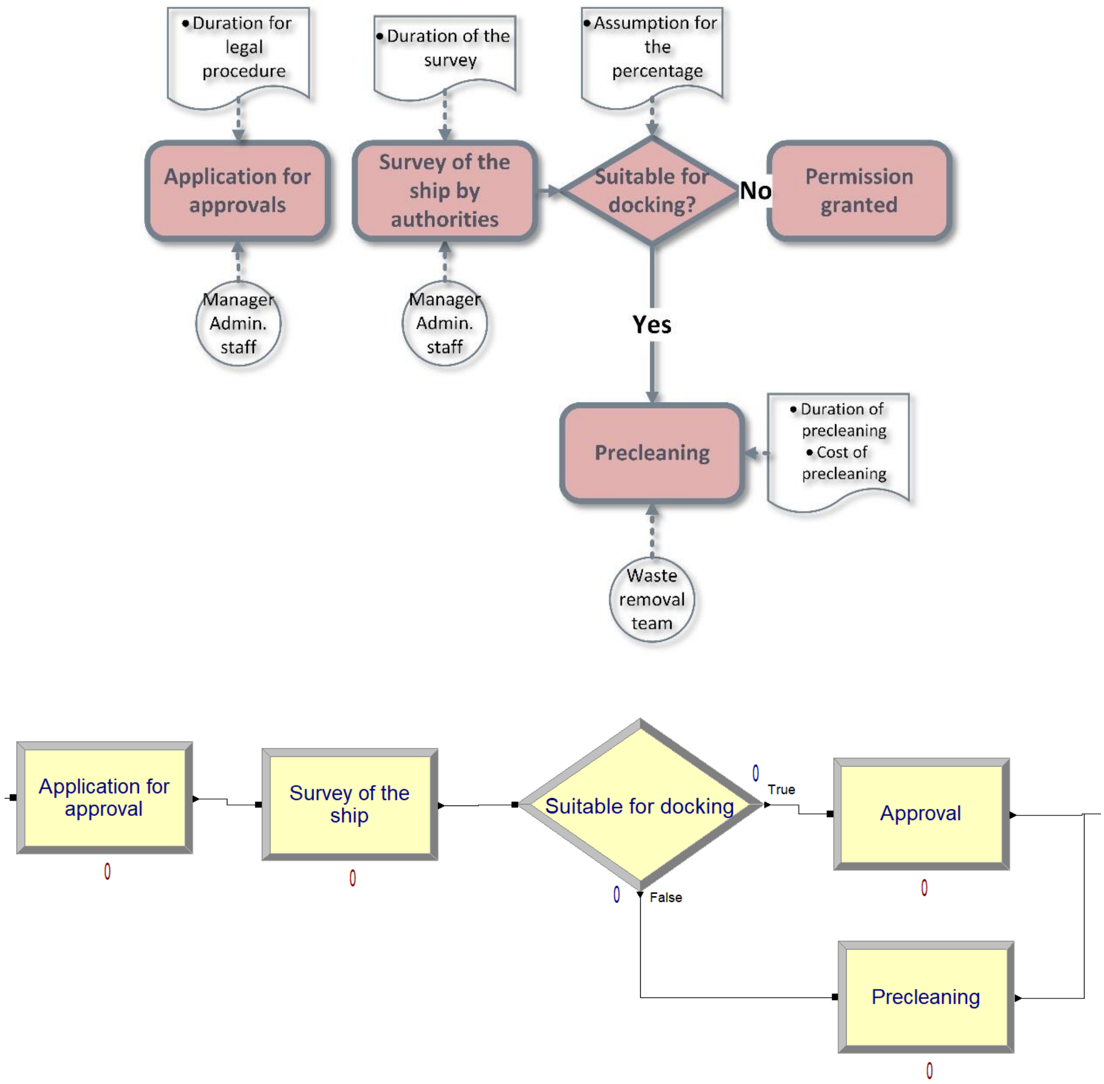


Figure 4.37: Administrative step - predock (above) and translated model in the Arena environment (below)

4.5.7 Docking

This model focuses on the docking of the ship. During the docking of the ship, depending on the ship's condition (whether it can self-propel or not), tugboats can be included in this step. The generic process of docking of the ship is summarised to two steps; docking of the ship, securing the ship and arranging access. Graphical representation and Arena modules for this step are shown in Figure 4.38.

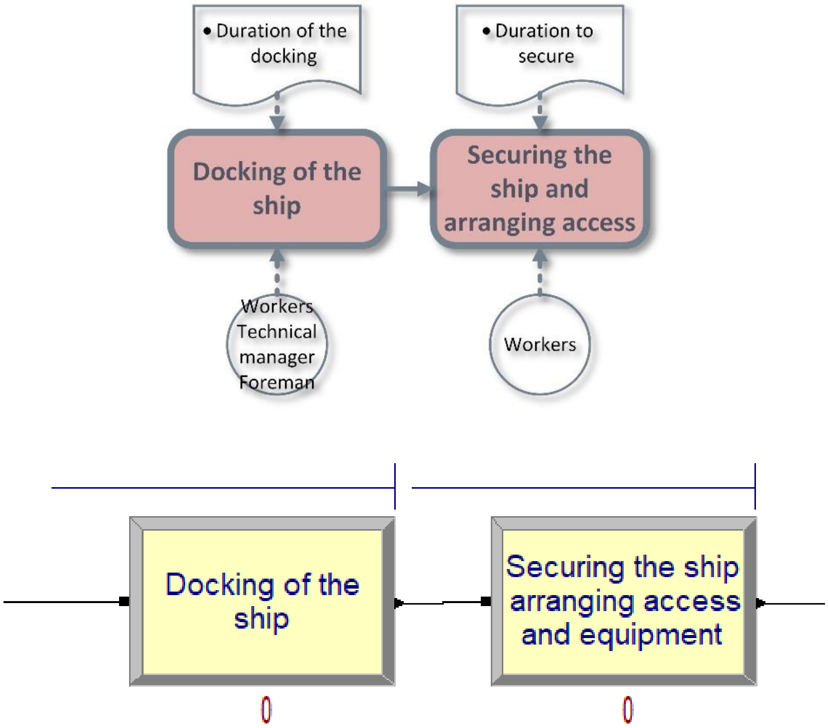


Figure 4.38: Docking step graphical representation (above) and translated to the Arena environment (below)

4.5.8 Preparation for recycling – shore

In this model, IHM survey is conducted, the ship is inspected for safety, general cleaning of the ship is conducted, hazardous materials are removed from the ship, liquid waste is removed, and finally quality check is done to ensure all the hazardous waste is removed from the end of life ship. The model is demonstrated in Figure 4.39.

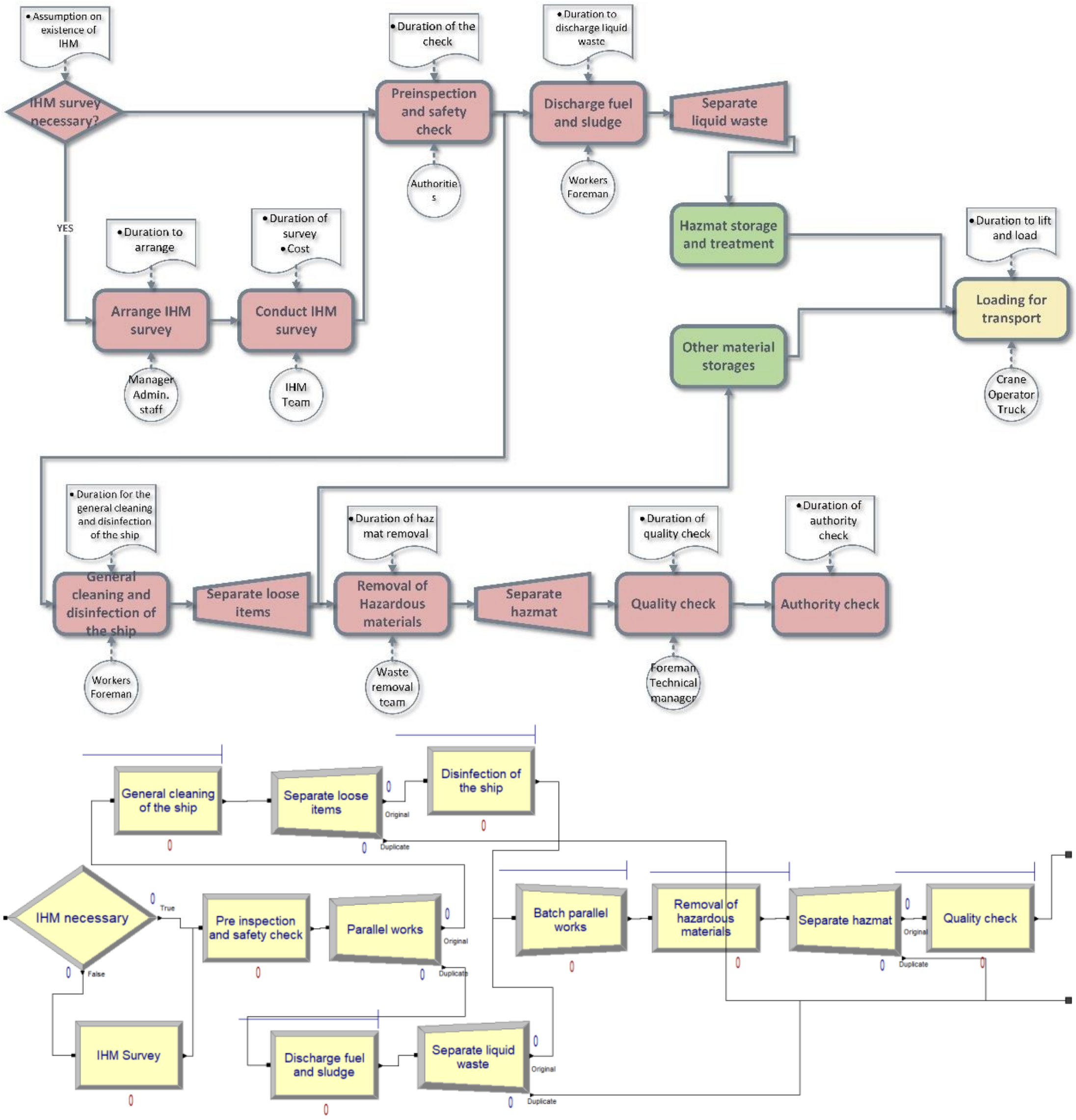


Figure 4.39: Preparation for recycled step graphical representation (above) and translated to the Arena environment (below)

4.5.9 Primary cutting and Removal of equipment and materials

Preparation for recycle step connects to two submodels; Primary cutting (and removal of equipment and materials), and Segregation and storage. This step will explain the approach in Primary cutting simulation model (Figure 4.40).

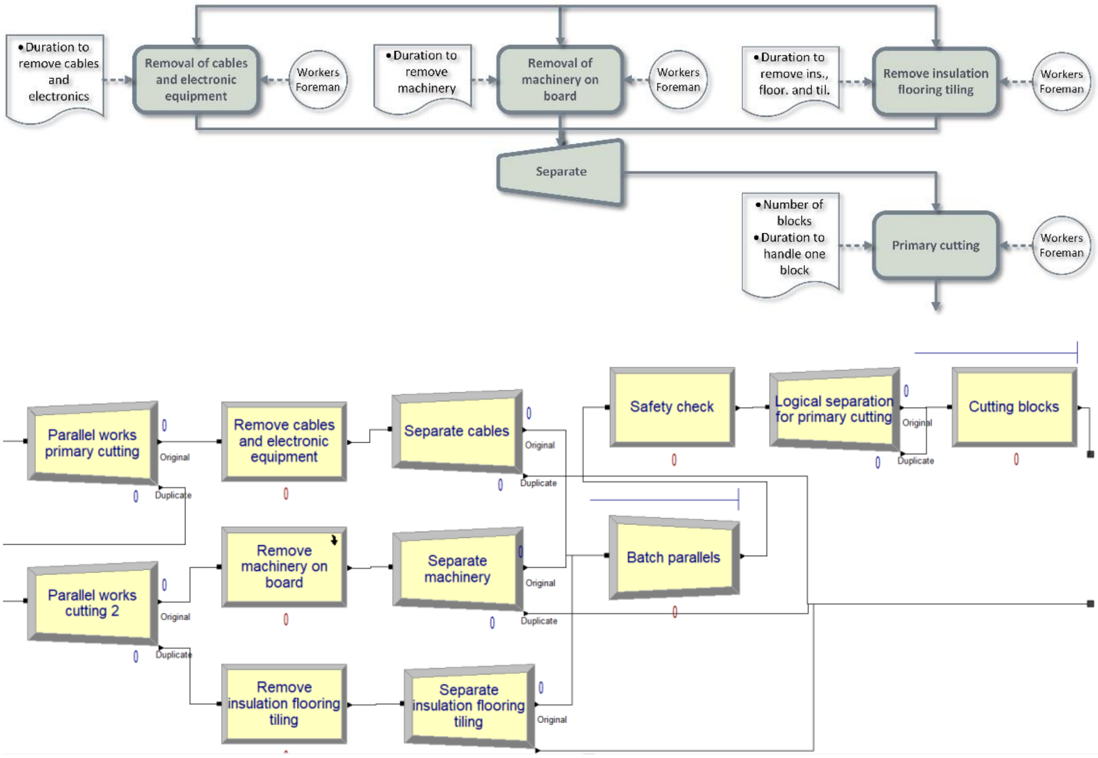


Figure 4.40: Primary cutting step graphical representation (above) and translated to the Arena environment (below)

Primary cutting step includes the dismantling of the equipment in the engine room. This process has been modelled as a separate model to accurately represent the operation for the removal of the equipment on board the ship. Details of the model can be found in Appendix B of this thesis.

4.5.10 Further cutting in secondary cutting zone

This model conducts the transfer of the blocks from primary dismantling zone to secondary dismantling zone and further dismantling of these blocks in the secondary dismantling zone (Figure 4.41).

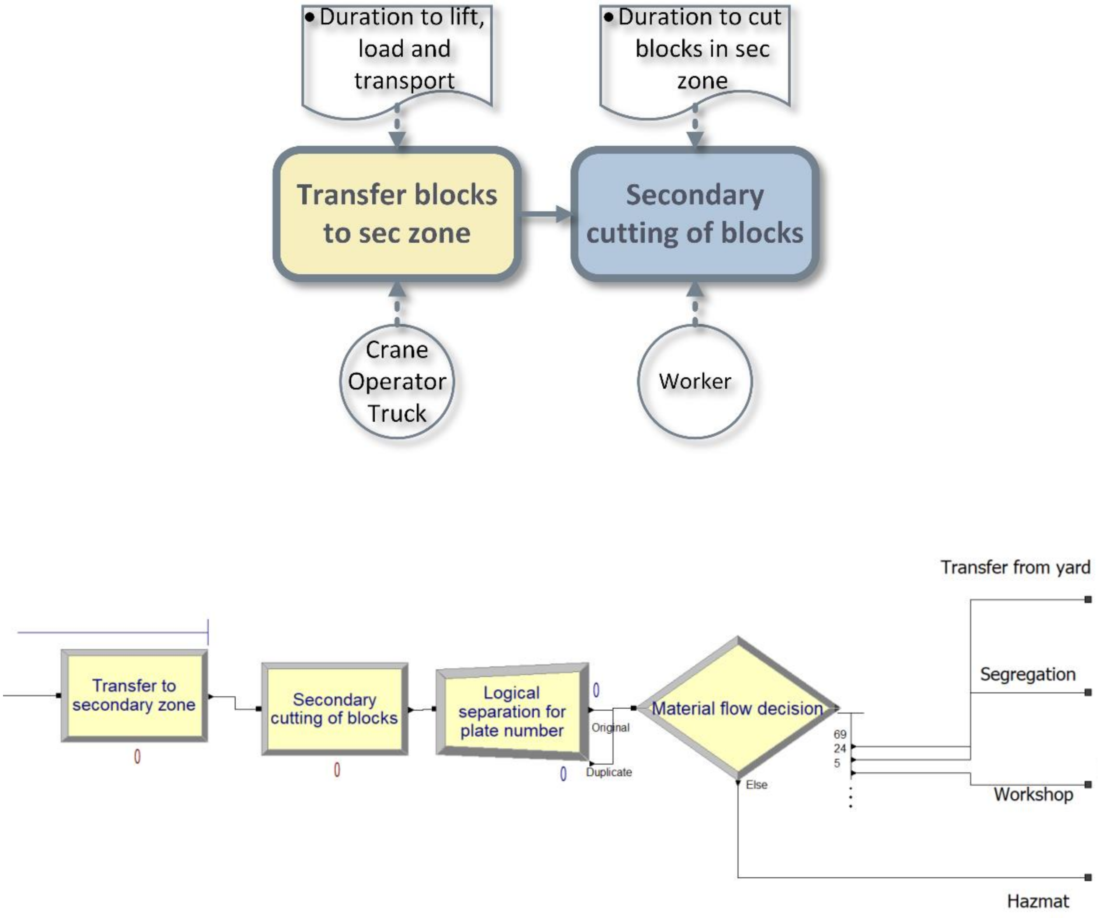


Figure 4.41: Secondary cutting step graphical representation (above) and translated to the Arena environment (below)

4.5.11 Segregation, Hazmat Treatment and Storage

Materials handled in Precleaning, Primary cutting zone and Secondary cutting zone are transferred to segregation zone for further treatment. These behaviour of these materials are demonstrated in this model (Figure 4.42). Additional Storages or material types can be introduced in this model if required.

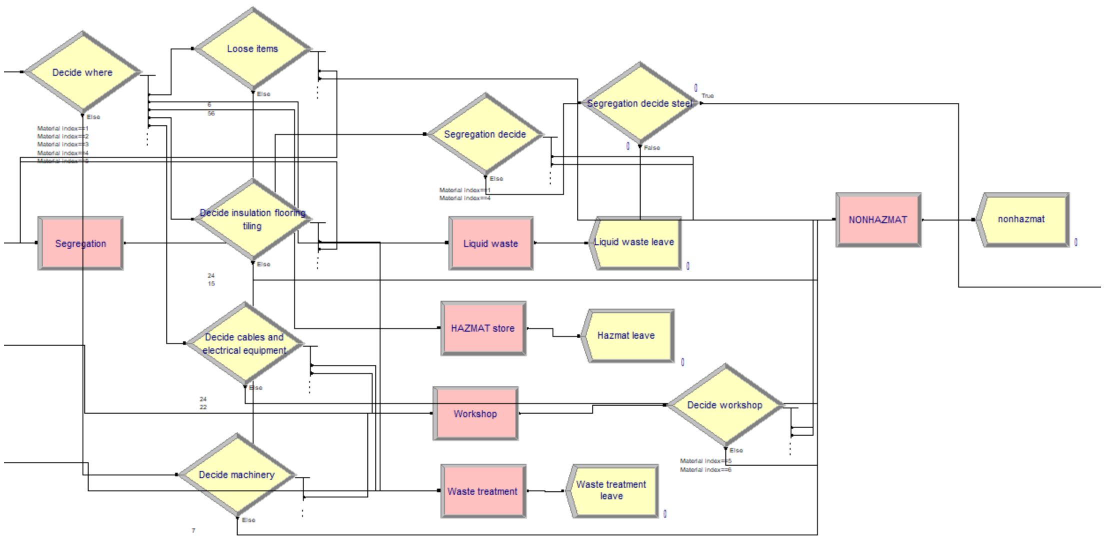


Figure 4.42: Segregation, Hazmat Treatment and Storage step Arena representation)

4.5.12 Transport out of the yard

The last step of the simulation model is the transport of the steel out of the yard. This model handles the loading of the materials from the yard and transports them out of the yard, in other words disposes the entities from the system (Figure 4.43).

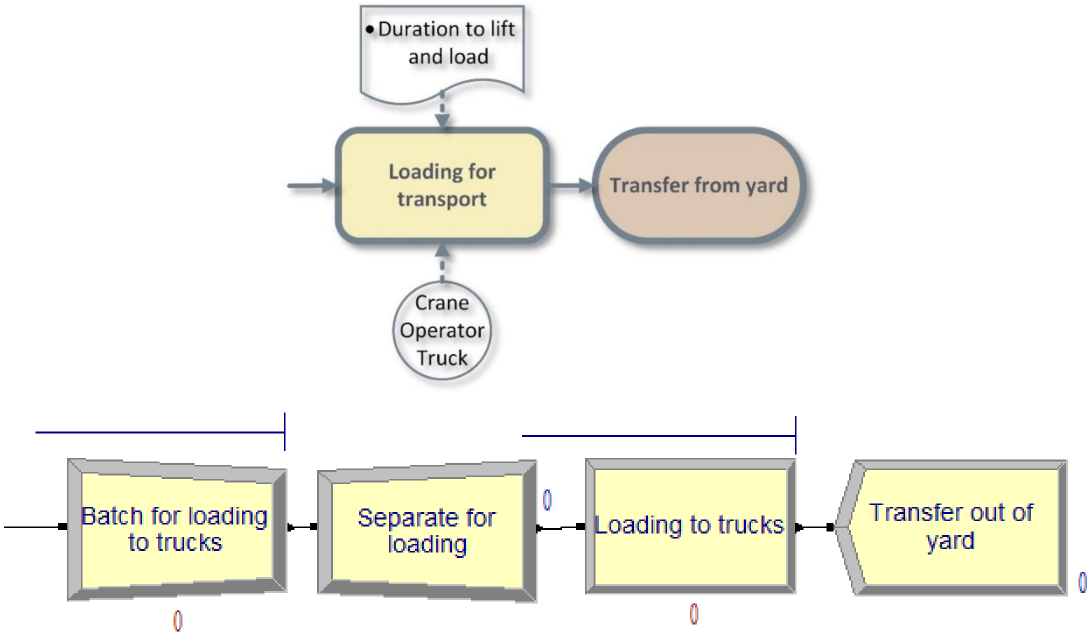


Figure 4.43: Transport out of yard step graphical representation (above) and translated to the Arena environment (below)

This section concludes the approach to overall model ship dismantling processes. The details, introduction and discussion of each step, data required for each step and resources involved in each step are summarised in Appendix C of this thesis.

Simulation model introduced in this section can be used to model the operations of an existing ship recycling yard to optimise the process, or it can be used in the (creation or modification of) design of a new ship recycling yard. Any modules in the simulation models can be removed (or added), combined with each other or order can be changed, in other words customised, to fit the needs of the case study investigated. The generated process models and models developed in the simulation environment are the first examples in the literature for ship recycling, therefore, these models make significant contribution to the literature. These models are also essential part of the *"Discrete Event Simulation Framework for Ship Recycling Facility Design and Optimisation"* (Chapter 5) that is developed as part of this PhD study. The developed framework will focus on the design and optimisation of ship recycling yards and utilise the developed simulation models to support the assessment and decision-making. The effectiveness of these models will be demonstrated through case studies based on real ship recycling yard in Chapter 6 and Chapter 7. In the next section, issues in the ship recycling processes that affects the productivity will be discussed to identify the factors and parameters to focus on in these case studies.

4.6 Identification of the Issues in Ship Recycling Yard Productivity

This section focuses on identifying the issues in ship recycling yards in terms are productivity, analyses the identified problems and summarises. The analysis conducted in this section for ship recycling yards is the first attempt in the literature. Therefore, apart from the context of this thesis, points in this section are crucial for the success and development of the industry in the long term. The key areas identified in this section will be investigated further in Case study Chapters to demonstrate that discrete event simulation approach developed as part of this thesis can increase the productivity of ship recycling yards and enhance the efficiency.

In order to identify the problem areas that affect the productivity in ship recycling yards, a comprehensive analysis of the operation in ship recycling yards were conducted. As part of this analysis;

- Site visits to different facilities in Bangladesh, France, Spain, and Turkey were organised. During the site visits, daily activities in the ship recycling (and boat recycling) facilities were observed to identify the bottlenecks and problem areas.
- Interviews and meetings were conducted with ship recycling yard owners and staff in order to benefit from their day-to-day experience. As a follow up to the site visits, contacts with ship recycling yard staff were made for further discussion on the identified problems in the yards.
- Findings of the previous research studies (especially EU funded DIVEST, ShipDISMANTL) were investigated. Previous research studies were also investigated further to utilise their findings in this study. Even though these projects are not directly related with the production performance of the ship recycling yards, some of their findings are valuable. Especially in the DIVEST project, state of the art of the ship recycling nations are summarised in a very detailed manner (DIVEST, 2009a). Problems in the HSE perspective were discussed comprehensively with measures to mitigate the problems. Since some of the problems are common for HSE performance and productivity performance, these reports are a good source of information.

In order to visualise the underlined causes of problem and also to include as many opinions as possible from experts, cause and effect diagram, which is also known as Ishikawa diagram will be used. Ishikawa diagram is ideal when identifying the root cause of the problem through expert judgement and identifying the bottlenecks of the operation (Ishikawa, 1982). Ishikawa diagram can be modified to fit different scenarios and circumstances, and it can be applied to any problem. The first step of the cause-effect diagram is the identification of the problem statement. Due to the focus of this PhD study, the problem statement is chosen as "slow production". The next step of the diagram is identifying the factors and the categories.

The categories in the cause-effect diagram are up to the analyst to decide. However, in this thesis, categories in different industries were also investigated to find the most suitable option for ship recycling industry. Suggestions on the categories for different industries were summarised in Table 4.3.

Table 4.3: Suggested categories for the Cause-effect diagram (isixsigma.com, 2013, smartdraw)

Service Industry	Service industry alternative	Marketing Industry	Manufacturing industries	Process steps
Surroundings	Policies	Product	Machines	Determine customers
Suppliers	Procedures	People	Methods	Advertise products
Systems	People	Process / Procedure	Materials	Purchase
Skill	Plant/Technology	Promotion	Measurements	Sell product
(Safety)		Price	Mother Nature (Environment)	Ship product
		Packaging	Manpower (People)	Provide upgrade
		Place / Plant		

When these categories suggested by different sources are reviewed, ship recycling can be considered as a manufacturing industry, therefore, categories suggested for the manufacturing industries can be used with a modification to fit better to the ship recycling industry. Manufacturing industry categories include machines, methods, materials, measurements, and manpower, however, considering the nature of the ship recycling industry, measurements and materials are not a good fit. Also, for the better understanding, machines were agreed to be changed as Equipment as both manual, and powered tools are in use in ship recycling facilities. Also, considering the other industries, safety and plant categories from the service industry are a good fit for the ship recycling industry. Therefore, it was decided to have six categories (factors) for this activity; Facility, Manpower, Method, Environment, HSE, and Equipment (Figure 4.44).

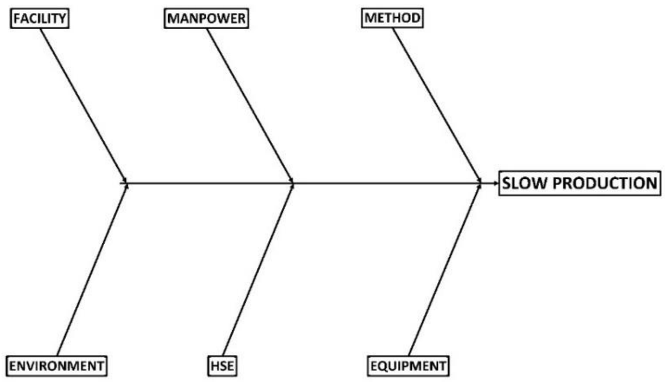


Figure 4.44 Cause and effect diagram template for ship recycling facilities

Facility: in this factor, the physical limits of the ship recycling facilities that are affecting the overall performance were included.

Manpower: In this factor, problem causes related to the workers were considered.

Method: Issues related to the ship recycling methodology are discussed in this factor.

Environment: Effect of the environment are included in this factor.

HSE: Safety measures for occupational and environmental health that slow the production were included in this factor.

Equipment: Effect of the equipment on the performance were discussed in this factor.

Next step after deciding the significant factors, was the identification of the possible causes for the slow production which were then placed under the related factor branch. The results of the observational study conducted, interviews, and workshops were utilised in this analysis and findings were included in the cause-effect diagram. The initial version of the diagram was discussed through the interviews and meetings and finalised as shown in Figure 4.45.

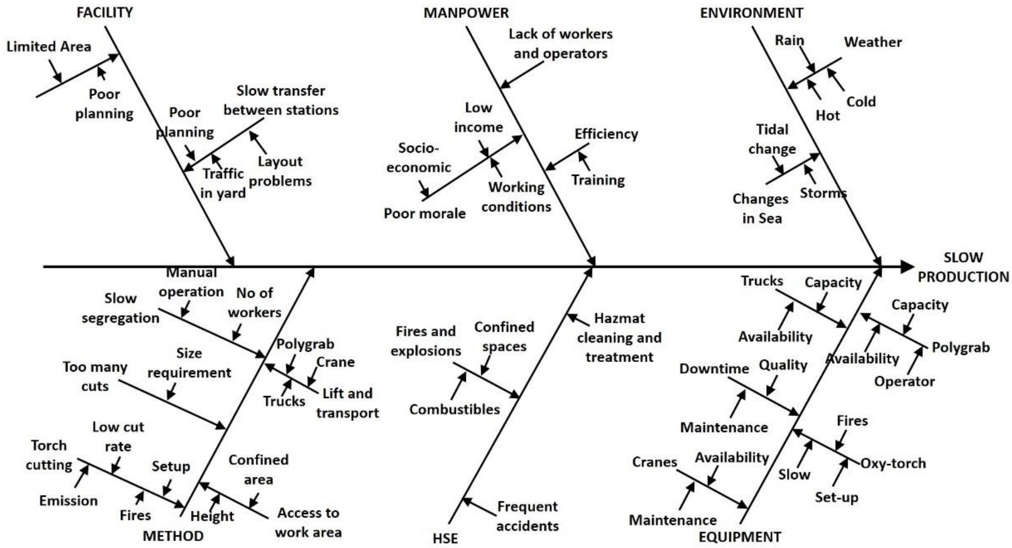


Figure 4.45: Cause-effect diagram for the ship recycling yards

4.6.1 Facility

In the facility category, the most important criteria are the size of the individual zones. During the planning stage of the yards, there is no comprehensive methodology to design the areas fit-for-purpose. Most of the time, secondary cutting areas are designed smaller than it should be which causes the production to stop in the primary cutting zone, as there will not be space to put the blocks for further cutting. This problem can be addressed through the implementation of discrete event simulation during the planning stage of the facilities.

Another problem in the facility category is the transfer of the materials (material handling) between the stations. Some yards do not have well organised layout which causes problem for the circulation in the yard. In addition to the layout problem, another factor that causes problem for material handling is the capacity of the transport equipment (e.g. cranes, polygrabs and trucks). Due to the high investment cost, yard owners tend to limit the number of transfer equipment and during the yard visits, it was observed that this was causing materials waiting for transport in piles and taking up space. Therefore, the case study that will be conducted as part of this thesis will focus on the optimisation of the layout using the discrete event simulation approach. In this case study, material handling will be also specifically focused on to come up with innovative solutions to such problems.

4.6.2 Manpower

Manpower is also one of the critical parts of the ship recycling operations. Since ship recycling is a labour intensive industry and the number of workers is an essential factor for the performance of the ship recycling yards. Using the discrete event simulation approach, the optimum number of workers can be planned for a ship recycling yard. Some of the yards have a low number of machine operators who are mostly responsible for operating the cranes, polygrabs or similar handling.

Therefore, it is important to study the number of workers, operators and other staff in a ship recycling yard to balance the costs and production performances. Number of staff employed in the ship recycling yard will be included in the simulation case studies.

4.6.3 Equipment

One of the most common operation in ship recycling yards is cutting of steel (Kurt et al., 2017). Yards are using oxy-fuel cutting (Acetylene, propane, LNG, and so forth) and even though it is cheap and easy to use technology, alternative production methods can improve the performance in the cutting operations. Therefore, alternative methods to the oxy-fuel cutting will be investigated and tested with simulation approach in the case studies.

Apart from the cutting method, a number of trucks, polygrabs, cranes, and operators of these machines were communicated as the bottlenecks of the systems. Therefore, the case study will also involve optimisation of the numbers of these resources.

4.6.4 Method

During the cutting process, oxy-fuel torches are being used by the workers due to the very low investment cost, low training need, and ease of operation. However, especially in the secondary cutting zone, performances of the cutters are very low. Thus, in the observed ship recycling yards, the secondary cutting zone was mostly the bottleneck of the system. When the area capacity of the secondary cutting zone is reached, production in the primary cutting zone has to be stopped as the blocks are transferred to the secondary zone once they are cut in the primary zone. This causes a delay on the clearance of the primary zone for the new ships which in the long term decreases the capacity of the ship recycling yard.

Torch cutting is mostly used in the current process to cut the steel into smaller pieces. The main aim of cutting the steel plates to smaller pieces not only transportation but also to fit the requirements of the steel mills. Different mills require the plates different maximum dimensions (e.g. 1x1x1meters or 1x0.5x0.5meters). However, the size limit of the mill increases the number of cuts, which increases the overall time and resource consumption. The alternative mills can be considered as a solution. In order to investigate this further, different cutting sizes will be investigated as part of the case study to see the effect of different cutting sizes of the plates.

Moreover, some of the sections of the end of life ships are covered with oil, fuel and other combustibles. Therefore, small fires due to the torch cutting were common in the visited ship recycling yards. Also due to the emission during the cutting job, workers need to stand with distance to each other. Treatment of the surfaces before cutting process and cold cutting methods can be considered as a solution to this problem. Therefore, a cold cutting method and a surface treatment option to the cutting process will be considered in the case study as well.

4.6.5 Environment

On the environment side of the issues are changes in the sea and weather effects can be counted. Tidal changes, storms or bad weather (too cold or too hot weather) can be given as example to the factors that have adverse effect on the productivity of the facilities as most of the tasks are conducted outdoors.

4.6.6 HSE

Accidents, fires and explosions frequently happen in substandard yards, Therefore, HSE measures should be in place before starting the operation. Setting these measures sometimes slows the operation, however, for the occupational and environmental safety, these measures are essential. Also, HAZMAT cleaning and treatment sometimes create a bottleneck as these operations are mostly dependent on external experts and cause a delay in the overall process.

4.6.7 The outcome of the cause-effect diagram

Even though every ship recycling yards is unique, cause-effect exercise helped in to understand the bottlenecks in observed ship recycling yards. The case studies for the discrete event simulation framework will be based on the outcomes of the cause-effect diagram. Focus areas of the case studies are shown in Figure 4.46.

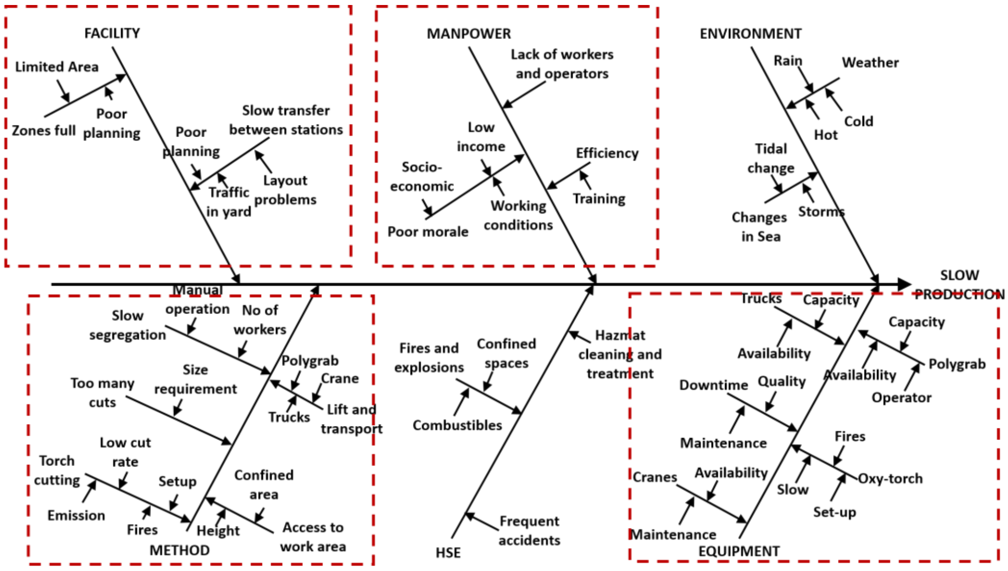


Figure 4.46: Cause-effect diagram

This thesis approaches the problem from the productivity side, hence, effects of HSE and environment will not be taken into account. Therefore, following factors will be considered

- Facility
- Manpower
- Method
- Equipment

Case study 1 (Chapter 6) will focus on the design on the ship recycling yard with focus on the design of ship recycling yard including area allocation, transfer between zones (stations), and different resource (worker, machines, cranes). This case study will also focus on the alternative approach on the steel sizes to see if it is economically feasible to increase the plate size that are transferred to the steel mills and if it is possible to increase the profit with reduced worker and torch times.

Case study 2 (Chapter 7) will focus on the application of different cutting technologies to ship recycling yards to increase the overall speed while increasing the overall profit margin of the yard.

4.7 Chapter Summary

This chapter summarised the operation procedures in the different ship recycling countries and compared these procedures to develop a standard ship recycling process flow. Then, simulation approach based on the standard process flow was summarised in this chapter.

Chapter 5 Discrete Event Simulation Framework for Ship Recycling Facility Design and Optimisation

5.1 Chapter Overview

This chapter presents a novel framework to develop and optimise a ship recycling facility using the discrete event simulation.

Ship recycling yard investment starts with the planning of the ship recycling yard and the construction of the facilities. Facilities and the overall properties of the yard should be planned and designed carefully to fit the purpose of the yard and to meet the goals of the yard. Better design of facilities will increase the production capacity of the yard through the better utilisation of yard area and resources as well as better material handling processes. However, approach to the design of ship recycling yards is close to primordial; facility layouts are developed according to the circumstances rather than proper planning and engineering approach. Review of the literature in Chapter 2 also showed that, studies in yard development for recycling yards are very limited.

This chapter will first describe the modelling levels, zones, and the system definitions for a ship recycling yard to define the limits of the layout development approach. Then, introduces the simulation framework for layout design of a ship recycling facility, and the optimisation approach to improve the efficiency of the yards.

5.2 Definition of Ship Recycling Yard System

In this section, the modelling levels and the system definitions for the ship recycling yards are introduced. In order to develop the system definition, all ship recycling methods have been investigated and commonalities were identified to produce the illustrative ship recycling system introduced in this section. This step of the framework is important because it defines the limitations and opportunities for potential improvement in the system.

5.2.1 Modelling levels for the layout design framework

Before going into the details of the layout framework, it is important to understand the modelling levels of the ship recycling facility. The modelling levels and descriptions are shown in Table 5.1.

Table 5.1: Modelling levels and descriptions presented (modified from ShipDismantl Project (ShipDISMANTL, 2009))

Modelling Level	Description
Ship Recycling Yard	Yard represents the overall system of a ship recycling yard, with zones and sub-zones integrated
Zones	Zones are the main areas in a ship recycling facility, separated by the activity type (Groups of sub-zones that perform similar or sequential functions or handle similar product stages form zones).
Facility	Represents an individual work-centre or storage area within a zone

Basel Convention guideline presents an overall idea on the ship recycling facility guidelines and introduces the zones. Zones that are introduced in the guidelines are (Secreteriat of the Basel Convention, 2003);

- Containment zone
- Zone A: Primary block breaking area

- Zone B; Secondary block breaking area
- Zone C: Sorting, finishing and overhauling areas
- Zone D: Storage areas
- Zone E: Office buildings and emergency facilities
- Zone F: Waste disposal facilities

Activities in the zones are shown in Table 5.2.

Table 5.2 Main Facilities and activities in the zones(modified from ShipDismantl Project (ShipDISMANTL, 2009))

Zone	Facility	Activity
Containment zone	Oil booms and spillage measures	Laying of oil booms to prevent spillage/pollution to sea
Zone A: Primary dismantling zone	Pier/quay/dock/slipway, cranes, winches, temporary storages	Block cutting, hazmat, other waste and equipment/machinery removal,
Zone B; Secondary dismantling zone	Cutting areas, sorting zones, hazmat processing area	Further cutting, initial sorting, hazmat processing, non-hazmat processing
Zone C: Finishing and sorting	Sorting area, loading area, hazmat segregation	Secondary segregation, loading for transportation
Zone D: Storage	Metal, non-metal, machinery, wood storages, loading zones	Storage of the metals, non-metals, other materials, equipment, machinery
Zone E: Support and offices	Offices, first aid, tanks	Emergency services, administration
Zone F: Hazmat storages	Hazardous waste storages	Safe storage of the hazardous waste

Representation of these zones in a conceptual ship recycling yard is shown in Figure 5.1, Figure 5.2 and Figure 5.3.

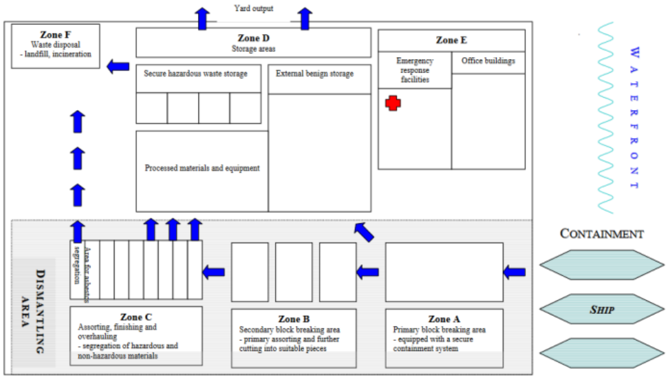


Figure 5.1: Conceptual illustration of a model ship recycling yard (Secreteriat of the Basel Convention, 2003)

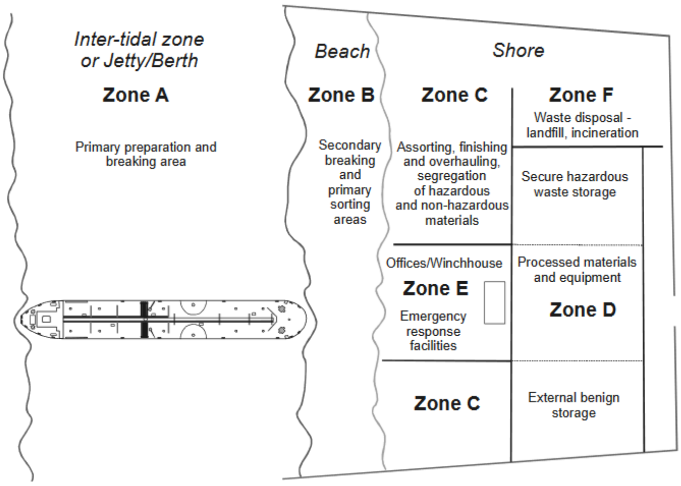


Figure 5.2: The zoning of ship recycling area(ILO, 2003)

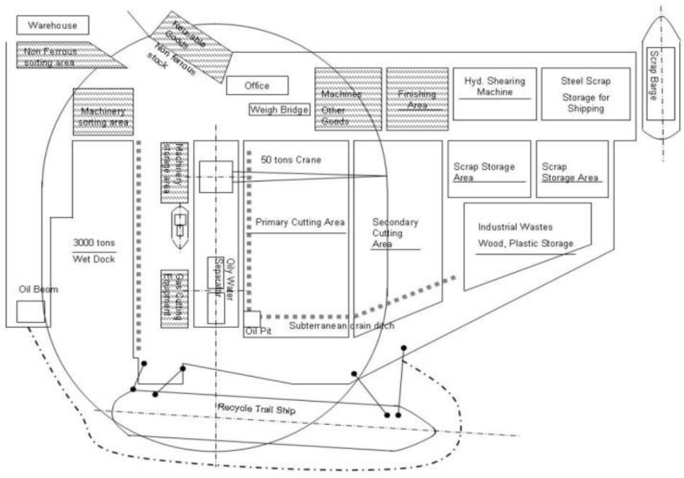


Figure 5.3: Yard plan example by IMO (IMO, 2012)

5.2.2 System Structure of a Ship Recycling Facility

In this section, interaction of the zones will be discussed through the developed system structure for a standard ship recycling yard. Ship recycling yard system was divided into two different supersystems, which are then divided into individual subsystems for analysis and comparison. These supersystem and subsystem structures are represented in Table 5.3. The major activities in these systems and interaction of these systems with regards to function and capacity is demonstrated Figure 5.4.

Table 5.3: Ship recycling system structure modified from (Shin et al., 2009)

Supersystem	Zone(s)	Subsystem(s)
Docking zone	Containment zone Primary Dismantling Zone	Docking system On board ship Cranes/winches/transfer units
Inland	Secondary dismantling zone Finishing and Sorting Storage zones Support and Offices	Cutting areas Temporary and permanent storage areas Segregation area Loading areas Traffic zones Hazardous material storages and Waste Treatment Office(s)

Docking zone supersystem of the ship recycling yard defines the maximum number of ships that could be handled at the same time in the yard. The end-of-life ships will be docked in this area and some of the processes (e.g. hazardous and non-hazardous waste removal and treatment, removal of equipment, and removal of machinery) are conducted here. Ship recycling process starts from the docking zone, therefore, it is important to address the docking area first during the design stage. In addition, transfer capacity from primary dismantling zone to other zones in the yard will be determined through the transfer units (e.g. cranes) that will be placed in this supersystem. Therefore it is also an essential factor to consider through the design stage.

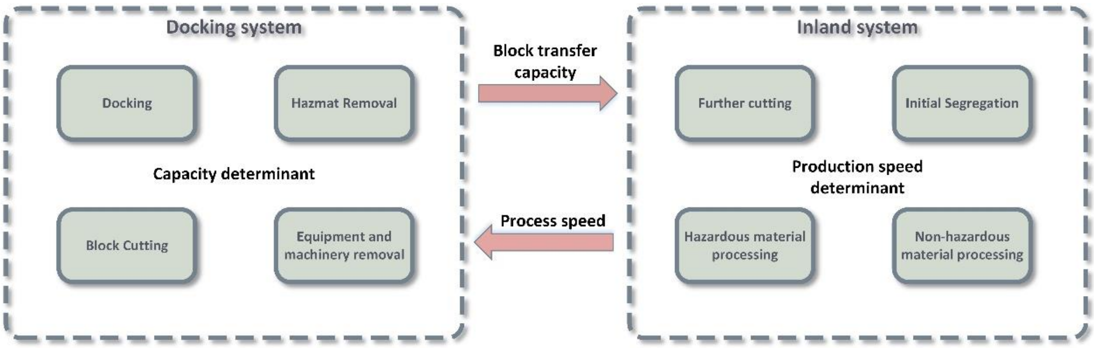


Figure 5.4: Definition of a ship recycling yard system and the interaction between these systems

Inland super system consists of secondary dismantling zone, finishing and sorting, storage zones, support and offices, and hazmat storages. Inland supersystem influences the performance of the ship recycling yard through the production speed in the zones. The process speed of the transferred blocks in the secondary dismantling zone is an important factor for the productivity of the ship recycling yards. If the blocks and materials are not handled fast enough, this supersystem becomes a bottleneck and the production in the primary dismantling zone needs to be slowed or stopped. Therefore, during the design of a ship recycling yard the zones in the supersystem should be designed carefully.

The findings of the system structure analysis pointed out the important factors to be considered throughout the design of a ship recycling yard. Therefore, these factors have been taken into account during the development of the framework for ship recycling facility design and optimisation.

5.3 A Framework for Ship Recycling Facility Design and Optimisation

This section presents the novel framework for ship recycling facility design and optimisation. The framework presented in this section will be the reference point for future ship recycling yard development and optimisation. The framework developed in this PhD study is novel because it reflects actual ship recycling procedures currently implemented in ship recycling yards globally. All these procedures were studied and observed in detail through numerous field studies and expert consultations as reported in Chapter 4. After studying the commonalities and the differences between different ship recycling methods, this PhD produced a generalised model for ship recycling process flow, which can be used by designers as a starting point.

The System Engineering Standard (ISO 15288-2015) "*establishes a common procedure for describing the life cycle of systems and defines a set of processes and associated terminology for the full life cycle of a system, including conception, development, production, utilization, support and retirement"* (ISO/IEC/IEEE, 2015). The approach in system engineering is high level and applicable to the life cycle of any man-made system including the design. However, it requires a high level of modification and adaptation. Moreover, although it provides the process for development, it has no component to support decision making. Due to these reasons, systems engineering approach has never been utilised in ship recycling.

The novel framework proposed in this thesis, builds on the aforementioned process models, introduces a novel a simulation approach which will support the ship recycling stakeholders in the development and facility improvement decisions by cleverly utilising the philosophy of systems engineering.

Another strength of this framework is its plug and play functionality. All steps of the ship recycling procedures are separately generated in Arena simulation environment. These simulation models can be recycled to create custom ship recycling scenarios which can be utilised by designers/researchers to develop and assess new yard designs as well as to run systematic optimisation study on existing yards. Furthermore, all development stages including data collection, data processing, model development in Arena, development of common ship blocks, technologies and resources are reported in detail so that designers/researchers can follow the same procedure or use the outputs where it is appropriate.

The developed framework consists of four main phases;

1. Study and Investigation phase
   - Requirement analysis and definition
   - System analysis
2. Primary design and analysis phase
   - Primary layout design
   - Primary simulation
3. Detailed design and analysis phase
   - Detailed layout design
   - Detailed simulation for optimisation
4. Decision making phase
   - Verification
   - Final decision

In following sections, details of the developed framework will be given. However, at this stage it is important to introduce the overall structure of the framework, which is presented in Figure 5.5.

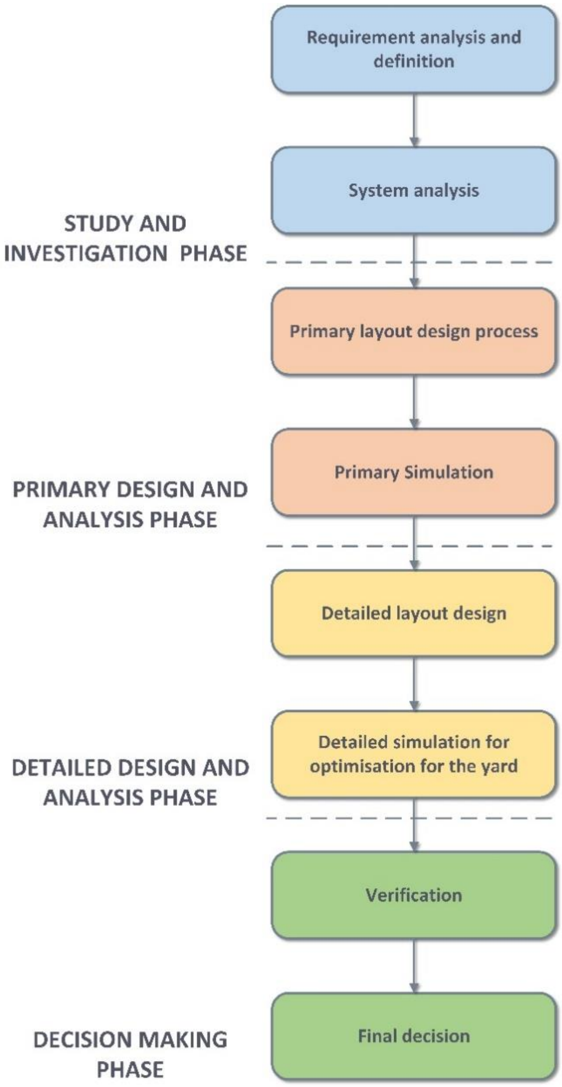


Figure 5.5: Phases and Steps of Design and Optimisation Framework

Developed framework can be used in different scenarios and what-if analysis for ship recycling yard development and optimisation. Through following different steps of the framework, ship recycling yard is capable of;

- Detailed Design and optimisation of a ship recycling yard from scratch
- Primary design of a ship recycling yard
- Layout/Facility Modification of an existing facility
- Optimisation of an existing ship recycling yard.

Phases and steps to follow for each usage category will be given next.

Detailed design and optimisation of a ship recycling yard from scratch

The framework is capable of guiding the user on the development and optimisation of a ship recycling yard. In order to design and optimise the yard, all steps of the framework, shown in Figure 5.5

Primary design of a ship recycling yard

The developed framework can also be used to make initial investment and capacity scenarios through the development of primary design of a ship recycling yard. The approach is shorter compared to detailed design scenario and should consists of three phases

- Study and Investigation phase
- Primary design and analysis phase
- Decision making phase

Layout/Facility Modification of an existing ship recycling yard

Using the framework it is also possible to make modifications on the design of an existing ship recycling yard. Phases the framework for the modification of an existing ship recycling yard are;

- Study and Investigation phase
- Detailed design and analysis phase
- Decision making phase

Optimisation of an existing ship recycling yard

In addition to the design midifications, proces optimisation of ship recycling yards is possible using the framework. The following phases should be followed;

- Study and Investigation phase
- Detailed design and analysis phase (only detailed simulation step)
- Decision making phase

Using the four different combination of phases and steps, it is possible to utilise the developed framework for various cases. The overall structure of the framework is presented in Figure 5.6. The details of each phase and steps will be explained in the next section.

5.3.1 Study and Investigation Phase

The study and investigation phase of the framework includes collecting the detailed information on the ship recycling yard requirements (e.g. owners expectations, data on the ship recycling yard's focus ship, yard's process and material flow). This phase comprises of two steps;

- Requirements analysis and definitions
- System analysis

5.3.1.1 Requirements analysis and definitions

Requirements analysis is the first step of the framework and it is used to understand the customer requirements, owner of the ship recycling yard, and to understand that "*what the system must do*" and "*how well it must perform*" (DoD, 2001). It must be ensured that the requirements are clear, comprehensive, complete, and concise as the requirements analysis must clarify and define functional requirements and design constraints.

Requirements are categorised in several ways. The common requirement categorisations are stakeholder (owner) requirements, performance requirements, and design requirements. Requirements in the layout design for ship recycling facility are divided into two different sections;

- Stakeholder (owner) requirements
- Review of laws, legislation and regulations

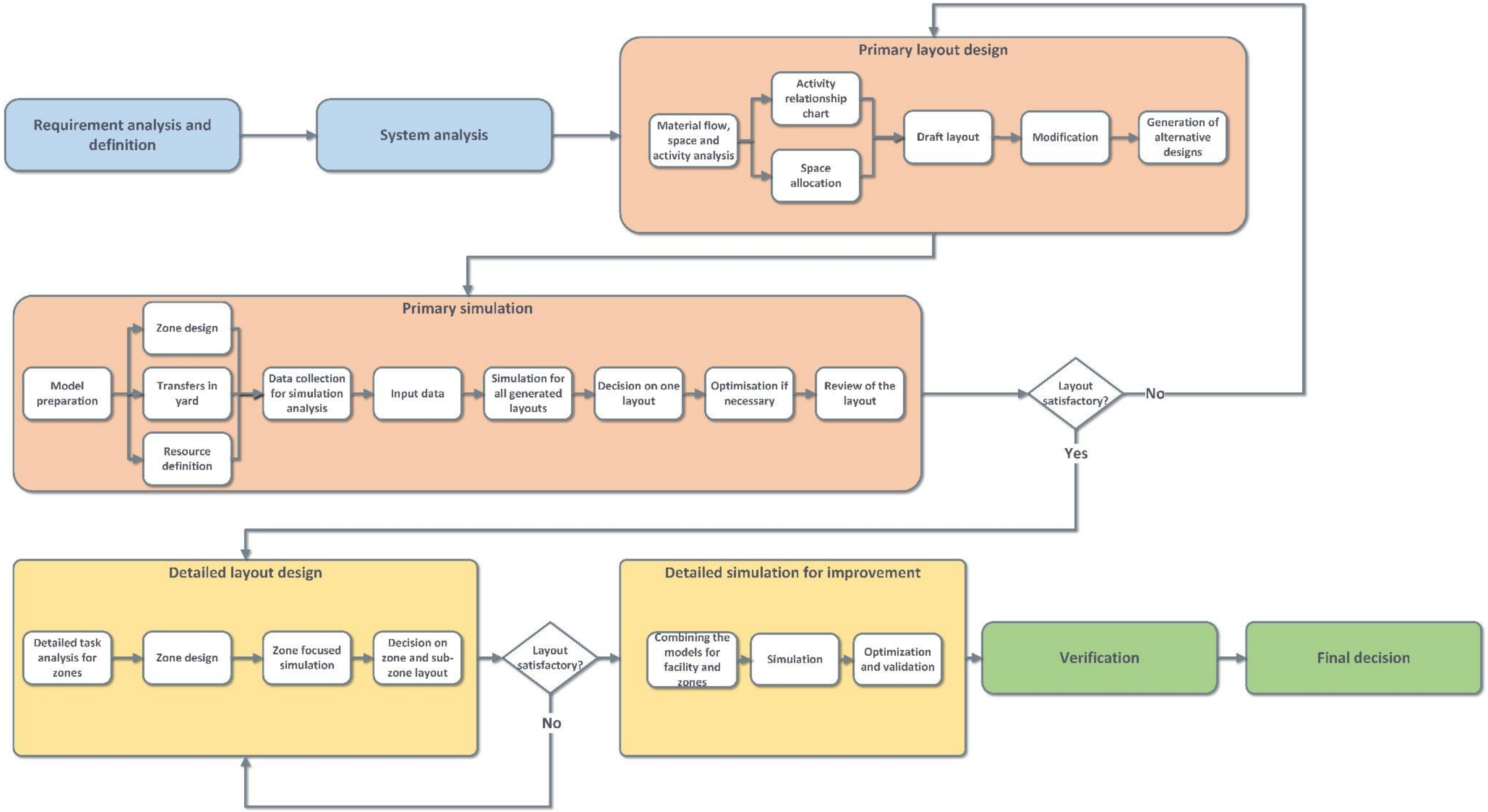


Figure 5.6: The overall structure of the simulation framework for ship recycling facility design

Analysis of stakeholder (or in this case the yard owner) requirements starts with the decision of the target ship type of the ship recycling yard. This might be dependent on the location of the yard (owner might be only targeting specific ships), the size of the yard (physical constraints of the yard), or laws, regulations, rules. Once the ship type is decided, next step is to decide the expected annual capacity of the yard. In addition to the capacity, process data, docking type and approximate resource numbers (workers, support staff, machinery, tools etc.) should also be collected from the owner at this stage.

Apart from the stakeholder requirements, laws, legislation, and regulation requirements are extremely important at this stage of the ship recycling facility design. Requirements of the IMO Hong Kong Convention, EU Ship Recycling Regulation, Basel Convention as well as local and national government should be investigated carefully as these will significantly affect the design of the ship recycling yard.

5.3.1.2 System analysis

In this step, characteristics of the yard are defined through the system analysis (i.e. the analysis of the production method, analysis of the physical environment of the yard and a basic capacity planning). Steps to follow are given in Figure 5.7.

First, all procedures are investigated in detail to define the specific needs of the processes. It should be noted that more detailed production method analysis will be conducted in the next stages, the process analysis at this stage is conducted to define the characteristics of the yard design and to define the major infrastructure required for the production method.

After defining the process range, next step is the analysis of the physical environment of the yard. This step can be conducted through site survey to gather detailed data on location of the yard (proximity to road and industrial zones), wind direction (for emission during cutting), geotechnical data (for the foundations of facilities), infrastructure (water, electricity, waste stream) and soil for the decision on the flooring.

The basic ship recycling yard capacity calculations can be done by identifying the total number of ships that can be dismantled yearly on average and maximum block sizes that can be carried from primary cutting zone to the secondary cutting zone. In particular, the basic capacity calculations start by the analysis of the target ships. Average/Maximum ship size which is defined in the requirement analysis step is analysed to decide the specifications of the docking area. Using the data, docking area required is calculated and dock is placed in the yard.

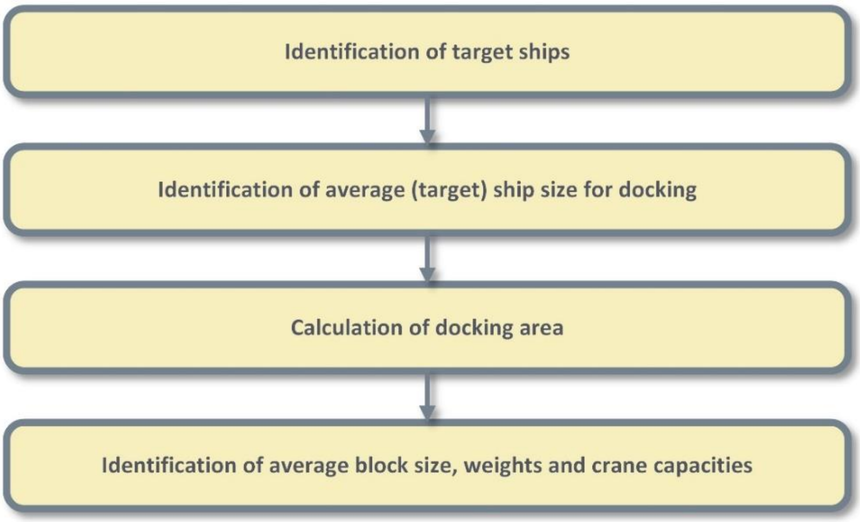


Figure 5.7: Basic capacity and area calculation for the zones

After deciding the placement of the mooring area in the yard, another important step is the decision on the average/maximum blocks sizes. The average/maximum block size can be found through the capacity of the crane/winch/polygrab (and additional carrying equipment if involved). The average and maximum block size will then be used to define the area needed in the secondary zone for the safe dismantling of the blocks. It should be noted that the condition of the ship and the structural elements, as well as complexity of the ship may influence the blocks size.

Upon completing the requirement analysis and system analysis, ship recycling facility design criteria area also defined. At this stage, following data is collected by the designer which can be called as “the ship recycling facility design criteria”;

- Target ships for recycling (ship type and size)
- Desired annual recycling capacity
- Physical constraints of the yard
- Approximate resource numbers and capacities
- Major facilities required
- Production processes and methods

5.3.2 Primary Design and Analysis Phase

Primary design and analysis phase utilises the information collected in the study and investigation phase and creates a rough draft with several alternatives through the steps provided. Following the development of design alternatives, this phase uses simulation to assess the alternatives to find the most suitable option for the requirements. The following two steps should be followed in this phase

- Primary layout design,
- Primary simulation

5.3.2.1 Primary Layout Design

Once the ship recycling facility design criteria is defined, primary layout design process can start. Primary layout design stage comprises of several sub processes;

- Activity analysis and space allocation
- Draft layout, modification and generation of alternative designs

5.3.2.1.1 Activity analysis and space allocation

In this step, activity relationship analysis for the ship recycling system will be conducted. Several different methods are available to conduct activity analysis and space allocation as introduced in the Chapter 2 of this thesis, but Muther's (1967) method is one of the best alternatives as it is commonly applied in similar sectors and provides an easy to follow method for analysis.

The relationship chart and activity relationship diagram

Activity Relationship chart (or diagram) is a vital technique in Systematic Layout Planning (SLP). The relationship chart is a form where the relationship between each activity/function/area and all other activities/functions/areas can be recorded. The basic version of this form is shown in Figure 5.8. The relationship chart shows which activities are related to others and the rate of importance of the closeness between them (Muther and Hales, 2015).

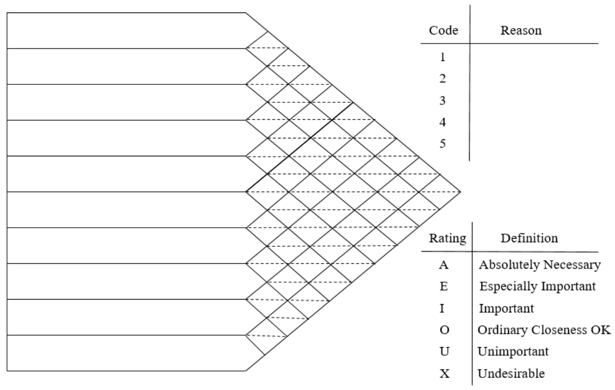


Figure 5.8: A basic "Relationship Chart"

The chart shown in Figure 5.8 is straightforward and self-explanatory. Analyst needs to write each activity/facility/area through the form in the horizontal boxes provided and then compare each activity one by one. Each intersecting box is divided horizontally into two different triangles; the upper triangle is where the closeness-rating is recorded while lower triangle is for the reason(s) of the decision on the upper triangle.

"Closeness" ranking for the upper triangle is rated according to a value scale "A, E, I, O, U, and X" which stand for;

- A Absolutely necessary;
- E Especially important;
- I Important;
- O Ordinary
- U Unimportant;
- X Not desirable.

Closeness rating should be combined with the reason of the rating in the relationship chart. Typical reasons supporting relationship ratings can include the following:

1. Flow of materials	7. Frequency of contact
2. Need for personal contact	8. Urgency of service
3. Use same equipment	9. Cost of utility distribution
4. Use common records	10. Use of same utilities
5. Share same personnel	11. Degree of communicative or paperwork contact
6. Supervision or control	12. Specific management desires or personal convenience

Analysts who might not be familiar with the process might tend to over-assign “A” ratings. In order to prevent this, the following frequency of rating occurrences from A through U are suggested; 2 to 5% A, 3 to 10% E, 5 to 15% I, 10 to 25% O. (the frequency of X depends on the project.

Space calculation and allocation

Once the maximum weight capacity of the crane, hence the maximum weight of blocks, are decided in the previous step, the approximate area of the block can be defined. Progress of the framework is shown in Figure 5.9, (boxes in green represents the steps completed so far while the yellow shows the new step). At this stage, a decision has to be made on the distance between cutters for safety in the secondary cutting zone. Through the maximum size of the block and the added “safety gaps”, several alternatives for the maximum number of blocks and the approximate area of secondary dismantling zone can be acquired.

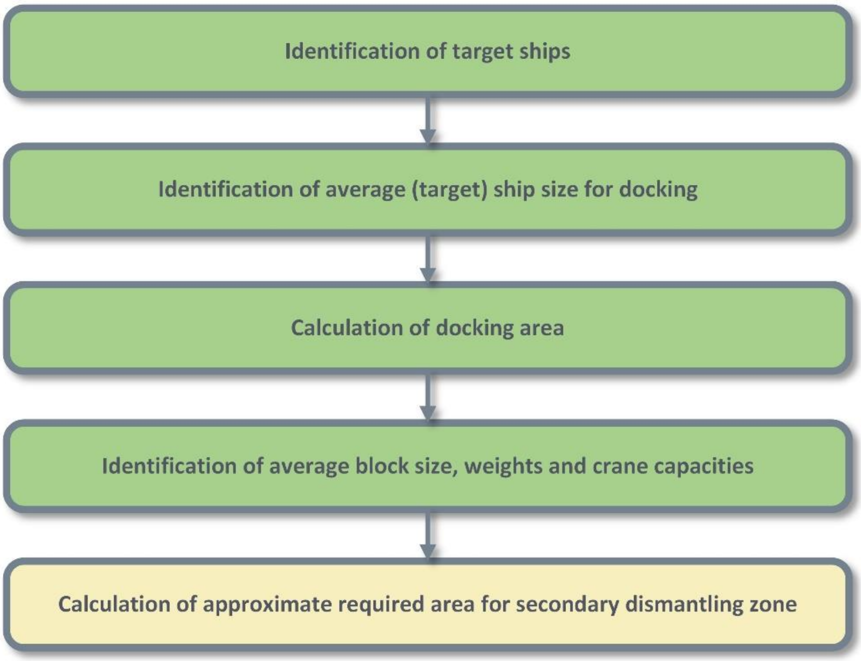


Figure 5.9: Basic capacity and area calculation for the zones

5.3.2.1.2 Draft layout, Modification and Generation of alternative designs

After completing the activity relationship chart and space calculation and allocation, activity relationship diagram can be drawn. Activity Relationship Diagram is basically a block diagram of the various areas to be placed into the layout. Therefore, it is a draft facility layout for the system under investigation.

The activities/facilities/areas are shown linked together by a number of lines according to the relationship chart. The representation of each relationship rating with lines is given in Table 5.4.

Table 5.4: Representation of the relationship rating in terms of lines

A	Absolutely necessary	
E	Especially important	
I	Important	
O	Ordinary	
U	Unimportant	
X	Not desirable	

The next step is drawing the activity relationship diagram using the lines shown in Table 5.4 to understand the distribution on the layout. After this, diagram is combined with the space requirement obtained in the previous step to form the “Space Relationship Diagram”. Once this step is completed, the diagram can be adjusted into a layout. To do so, the space required for each section should be integrated with the activity relationship diagram. Once the space required and the relationship diagram are combined, a draft layout that will need adjustments to allow additional features (e.g. access ways). After these configurations, several alternatives can be created using different combinations of the combined diagrams. When these alternatives are generated, the next step is to decide the best alternative for the layout. In this step, analyst may decide to put different criteria to find the best layout. Each design may have its own specific advantages and/or disadvantages. The problem is to decide which of the alternative plans is best fit for the purpose. Simulation approach can help the analyst to compare these layouts in terms of resource utilization, work in progress, transfer times, costs, cost-benefit or different criteria that can be defined.

5.3.2.2 Primary simulation

Simulation approach for ship recycling industry that was introduced in Chapter 4 of this thesis can be implemented to evaluate different layout alternatives generated in the previous step. Simulation models developed in this chapter can be customised for any ship recycling facility and utilised in the decision making of this step. First, the ship recycling process or planned procedure should be investigated. Next, a simulation model that represents the concept ship recycling yard should be prepared through using the models (or through following the model development method) introduced in this thesis. After the model preparation the analyst should collect the data depending on the depth of the model. Data collection should follow the guidance on data requirement for the given simulation steps in Appendix B. Data collection the includes the following (but not limited to);

- Costs for workers
- Initial and running costs of equipment
- Equipment manufacturing rate
- Process times for each step
- Transfer times
- Zone areas
- Typical delays in the operation
- Maintenance delays
- Failure rates
- Set-up times
- Maintenance costs
- Inspection durations

Following the data collection, next step is preparation of the input of the data to for the developed models and validation of the model to prevent any mistakes during the analysis. After the data was input, simulation runs for all generated layouts should be performed with different parameters to decide the most effective layout according to the selected criteria.

Following the decision on one layout, analyst may decide to optimize the selected layout for a better performance, in this step current model of the system should be modified and run again to maximise the yield from the yard.

After the selection and optimisation, selected layout should be checked if it is supporting the yard to reach its annual dismantling volume and to generate the income to profit (and to return the investment put in by the yard owner). Moreover, selected layout should also be checked in terms of HSE and the existing regulation. HSE analysis of the shipyard layout design is not in the scope of this thesis (but it will be included as a future study), but it is important to conduct a risk assessment for the selected layout considering the hazardous nature of the ship recycling industry.

5.3.3 Detailed Design and Analysis Phase

Framework crates a working draft design until this phase which can be utilised to make initial investment decisions. However, for more detailed analysis are needed, the detailed design and analysis phase should be followed. This phase has the following steps

- Detailed layout design
- Detailed simulation for optimisation

5.3.3.1 Detailed layout design

Using the previous steps, a layout which can be satisfactory for most of the ship recycling projects can be generated. However, if more detailed layout is needed, further improvement process can be followed. Similar to the basic layout design, the detailed task analysis for zones and subzones should be conducted (if it has not been conducted previously).

The first section of the layout design aims to generate a draft design for the zones. In this step of the framework, zone designs should be detailed with the arrangements of equipment, workstations and other facilities, such as traffic zones, loading areas, segregation areas, in these zones, and their relationships with other subsystems.

In the zone design, same steps in the basic layout design can be repeated specifically for each zone. Only one zone should be handled (strictly) each time to avoid confusion, with focus on equipment, machinery, facilities, workers and other resources in each zone. During the detailed zone design, constraints of the overall layout should be kept in mind to prevent errors in the overall design. Zone design should also be conducted at a slower pace to cover every detail.

Table 5.5 represents a capacity planning list for the detail design of major zones (that are related to production) in a ship recycling facility.

Table 5.5: Capacity planning for major (production) zones in a ship recycling yard

Zone	Capacity Planning Checklist
Primary dismantling zone	• Docking process and capacity analysis of pier/dock/slipway • Crane/winch or other lifting equipment placement • Facility for treatment of water from the drains (if existing) • Placement for loading/unloading areas, if trucks involved design of the maneuver and traffic areas • Relationship analysis for sub-zones • Maximum block size calculation (considering the cranes' lifting capacity) • Decision on the equipment and machinery to be used • Decision on the workforce; teams, individuals, supervisors etc.
Secondary dismantling zone	• Standard cutting capacity fixing to handle the transferred blocks • Decision on the equipment and machinery to be used • Decision on the workforce; teams, individuals, supervisors etc. • Relationship analysis for sub-zones • Decision on the areas to be included • Detailed calculation of the areas • Arrangement of block dismantling areas with the minimum safe distance between blocks taken into account
Segregation zone	• Detailed calculation of the areas • Decision on the material flow (which is sold directly, which is segregated, which is stored) • Decision on waste treatment, which will be treated internally, which will be stored for external treatment • Placement of storage areas (including hazardous and non-hazardous material storages) • Resource arrangement for transfer equipment or vehicles

After the design this table can guide the analyst/designer to double check the design process.

Sub-zone area allocations

Similar to the procedure in the basic layout design a guide for the analyst in the allocation of sub-zone areas is provided. Previous steps of the framework provides a rough plan for the overall layout but for more detailed plan following analysis and decision steps need to be completed.

Figure 5.10: Detailed capacity and area calculation for the zones

- Decision on plate size and hauling area calculation

Ship recycling yards cut the steel plates according to the technical requirements of the steel mills. For the detailed planning, which mills the steel will be delivered to can be decided in advance, and , the plate size of the cut steel can be decided accordingly. Using the size, hauling area for the cut steel before transport can be calculated.

- Calculation of in-yard loading and transport routes

Transport routes and loading-unloading areas should be detailed in this step. Most of the current yards are not planned properly for in-yard transport, which affects the productivity as well as safety of the operations. Therefore, these areas should be planned as well.

- Quantification of storage areas

Another essential step of detailed planning is the design of the storage areas. Basic design only deals with the general storage area design, however, individual storages for hazardous wastes, non-hazardous wastes, sellable goods from the ship, metals, electronics and other materials are essential and required. At this step, assumptions should be made according to the ship type and the number of materials/wastes for this type of ship. Several methods are available to estimate the material flow to design the facility including Andersen et al. (2001), Demaria (2010), Hess et al. (2001), Sujauddin et al. (2015a) and Jain (2017).

Throughout these steps activity relationship chart, activity relation diagram and other techniques explained in Basic layout design can also be used to generate the zone layouts. Once these steps in the Basic layout design are conducted for each zone, several alternative layouts for zones should be created. Following the generation of alternative layouts, a decision should be made on the best layout and zone focused simulation should be conducted separately for each zone to support the decision-making process.

Using the simulation, production performance of each layout can be obtained. Following this, occupational and environmental health safety analysis should also be conducted to understand the effect of layout on these aspects to avoid any potential negative impacts.

Even though zones may operate perfectly in isolation, they may not interact well with other zones within the big picture. Therefore, once the layout of every zone is detailed and decided, simulation that covers the entire operation should be conducted where possible and practical. Models from the zone simulation and the model from the Primary Simulation step should be combined in this step and these simulation results should be analysed in detail by the designer. If the simulation results are logical in the previous step, system can be investigated for further improvement. With this step, the design of the ship recycling yard finishes. If no further improvement is required, the next step can be skipped and steps seven and eight can be completed.

5.3.3.2 Detailed simulation for optimisation

This step focuses on the optimisation in the processes within a ship recycling yard. Improvement in the productivity can be achieved through changing the parameters of the processes and the yard. Step 1 of the framework outlines the requirements from the ship recycling yard and defines the goals in a defined time period. In order to reach these goals, further optimisation should be conducted. Ship recycling yard operations cover a wide range of different activities. The system should be investigated carefully to understand the cause of the issues. Following the identification, solution to the productivity issues can be found through the simulation. Using the simulation models, production performance can be improved through the modification of following parameters,

- Different Resource numbers

  Optimisation of resources is not conducted in the ship recycling industry commonly. Using the simulation approach, different resource combinations can be tested. A number of various worker numbers, in-yard transporters, crane capacities, Polygrab or operator numbers are one of the few examples that can be done. Altering the number of resources in the yard may contribute positively towards achieving the production goal. The simulation approach can demonstrate the effect of the change of resources on the performance. Moreover, using the simulation, effect on the cost and revenue of the yard through a selected timeframe can be calculated.

- Different technologies

  Use of different technologies, machinery or tools can be implemented to ship recycling operations. For example, ship recycling yards are mainly using the oxy-fuel torches during the daily tasks but alternative approaches can be considered to improve the performance.

- Alternative process approaches

The approach of the operation can be changed. For example every steel mill has different technical requirements for steel and different price offers. Yards mainly consider the highest offer or the proximity even though the mill requires smaller piece than other mills to maximise the overall performance in terms of profit. However, the difference in the size of the plates will affect the torch time (hence energy usage), worker time and emission. Also different docking methods, change in material flows, additional steps can be simulated. Therefore, cost-benefit analyses are essential for the right decision making.

- Ship arrival times, ship types

Different ship types and ship arrival times can also be considered to meet the defined goals.

Through changing these parameters and simulation, an estimate output of the ship recycling yard can be done. Apart from the production performance analysis through simulation, HSE analysis of the system should also be conducted in the big picture to understand the system's dynamics as a whole and the interaction between different groups regarding health and safety.

5.3.4 Decision Making Phase

In this step, developed design should be verified and final decision should be made based on the data collected, analysis and assessments conducted throughout this phase.

5.3.4.1 Verification

After the simulation step, an overall verification step should be conducted to check whether the ship recycling yard is able to meet the initial goal set in the requirement analysis step. Table 5.6 shows the basic check list for the ship recycling yard layout design that needs to be checked, validated, and generated.

Table 5.6: Checklist for the supersystems (Modified from (Shin et al., 2009))

Level	Contents
Yard layout	Location of each zone and interrelationship of these zones Size of each zone Process and material flow
Docking	Placement in the yard Logistic routing path design in the zone, roads, loading/unloading areas Storage of valuable materials in zones Equipment and facility placement
Inland	Placement in the yard and placement of zones in the inland supersystem Zone area and plan capability Important materials storage in zones Logistics routing path design in the zone / loading/unloading areas

5.3.4.2 Final decision

Following the design process and verification, final decision is up to the stakeholder. Analyst should provide the stakeholder with the outcome of the current layout (and the alternatives if exist).

The final decision concludes the framework developed in this thesis. In the next chapter, developed framework will be tested in a case study and design and optimisation of a ship recycling yard will be demonstrated using the framework and discrete event simulation method.

5.4 Chapter Summary

This chapter presented a systematic approach to the development and optimisation problems of a ship recycling facility using the discrete event simulation. This chapter first investigated the layout planning methods, developed a framework for ship recycling yards and then integrated simulation to this framework to design and optimisation of a ship recycling facility.

Chapter 6 Case Study on Ship Recycling Yard Design and Layout Optimisation

6.1 Chapter Summary

This chapter presents the application of the developed framework and the approach for a case study in an EU ship recycling yard. First, Initial layout and process plans for the ship recycling yard are investigated along with other criteria such as the shipyard's goals of annual scrap volume, number of staff, development plans for the future, constraints of the facility and so on. Next, planned process plans are modelled in the simulation environment, and bottlenecks with the current processes are identified. In order to solve these problems, various solutions are proposed and tested in the simulation environment to optimise the process. Different layout options, area capacities, different resource numbers and different techniques are modelled and tested for the shipyard as a case study.

6.2 Case Study Development

The ship recycling yard which is used as a case study in this section, has acquired all the necessary approvals from the local government. The owner of the yard is a well-known member of the ship recycling society for his approach in green ship recycling. The owner aims to design a yard that will be a role model for the ship recycling industry with the layout approach, technology and methods so that it can be scaled and/or transformed to any size or to any location. The yard aims to achieve this goals through;

- Reducing the costs by continuously developing the technology used and increasing the efficiency through minimisation of waiting costs by defining a perfect process line that will ensure everything and everyone is on duty all time and no time is wasted by workers or machinery through optimisation studies.
- Maximising the recovery of materials and equipment from end of life vessels especially from waste electric and electronic equipment and increasing the rate of recycling to reduce the waste sent to landfill or incineration. Also, rate of reuse will be increased through local and international second hand markets
- Exceeding all standards; yard comply with all conventions and national and international regulations on environmental issues regarding waste generation and job safety.
- Following the best practicable environmental options and protection methods. Harbour will be continuously monitored to prevent any harmful impact to the environment. Also, hazardous wastes and materials on board the ship will be handled by trained experts to minimize the damage it causes to environment and human.
- Creating awareness on job safety by prioritising the occupational health and safety on day-to-day tasks of the yard.

There will be other services provided along with the ship recycling services, such as

- Management, treatment and disposal of wastes from the recycled vessels and from other harbour activities, companies & vessels,
- Support for salvage of vessels in emergencies,
- Offer safe refuge harbour for vessels under trouble.

The framework developed in Chapter 5 will be applied on the development and design of this yard to represent the process in actual ship recycling facility design as well as to improve the framework through a case study.

6.2.1 Study and Investigation Phase

6.2.1.1 Requirement analysis and definitions

Requirement analysis was conducted through an interview with the ship recycling yard owner. Following the interview, an estimate on the customer requirements was established. The main goal is creating a state of the art sustainable ship recycling yard which integrates waste management facility within. The most advanced techniques, methods and technologies usable for ship recycling and compatible with the local and international laws and regulations were taken into account during the initial design of the yard. The procedures used in the yard will be optimized continuously and methods will be kept up to date to ensure a sustainable business that is environment friendly, safe for workers and efficient.

The initial estimation of the investors for the yard is that the yard is expected recycle 30,000 LDT scrap volume yearly, but the owner would like to achieve 60,000 LDT scrap volume (In other words, 12 medium size vessels of 5,000 LDT).

Main market focus of the yard will actually be the vessels that are out of ship recycling scope (vessels that are smaller than 500 GT, 27,084 vessels according to EC report (COWI, 2011)) and the medium sized ships which are between 500 and 25,000 GT (Approximately 36,000 ships according to aforementioned EC report (COWI, 2011)). This means in the future, approximately potential 45 million GT of ships will need to be dismantled. Ship recycling yard’s market will be primarily ships which have links to Europe through flag state or parent companies. This is generally estimated to be 40% of the world fleet with Greece, Norway, Germany and the UK having the main share.

6.2.1.2 System analysis

The port that yard is planned to be located is equipped with most modern facilities suitable for handling the traffic. Yard will be located in sheltered waters and the access is possible all year round. In order to understand the facilities that are required in the yard, ship recycling process plan should be understood first.

6.2.1.2.1 Planned ship recycling process of the yard

Ship recycling is a very complex business and the processes below may need to be modified for different type of ships but in here a generic recycling approach can be given. Yard's ship recycling approach has been divided into six main steps as follows;

- Administrative Step
- Preparation of the ship for recycling
- Primary cutting – floating
- Transfer to the ramp and secondary breaking
- Secondary cutting zone
- Treatment of fluids and residues

Flow of this process is shown in Figure 6.1.

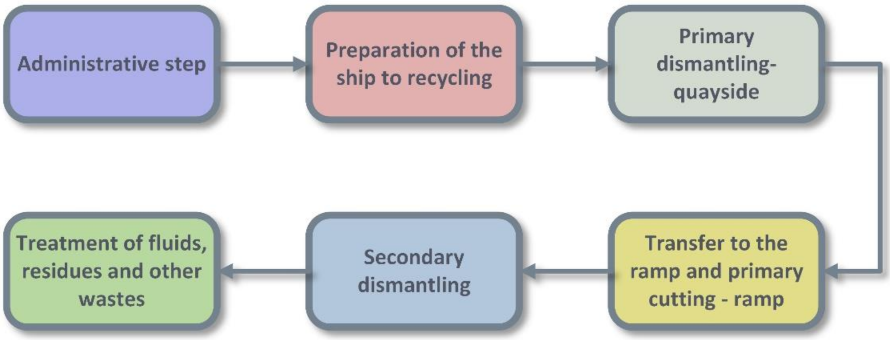


Figure 6.1: Basic diagram of process flow in the case study yard

Administrative work

First step of the recycling a ship is the administrative work. Administrative work starts from the acquisition of the ship from the owner and this step may vary on depending of the owner, type of vessel, terms of the contract, system of acquisition etc. Process flow of the administrative step is given in the Figure 6.2.

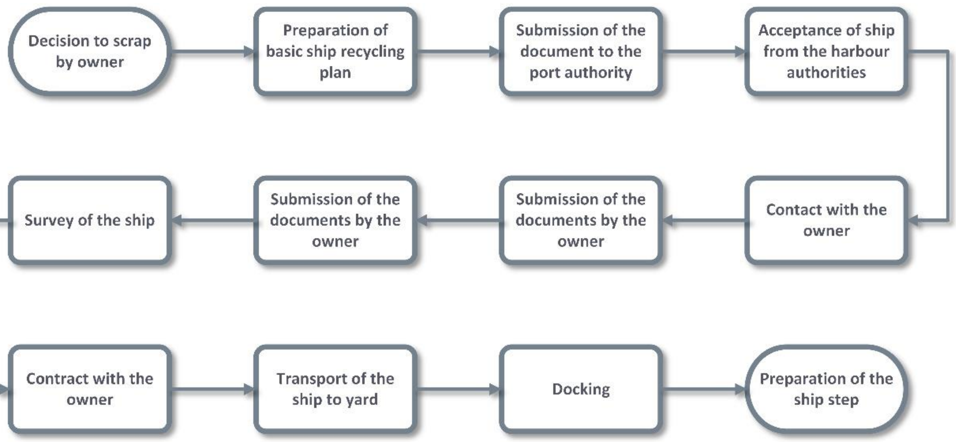


Figure 6.2: Process flow for the administrative step of ship recycling

Yard aims to have the capacity to handle any type of ship when the ship recycling yard becomes active. The only limiting criterion for the ship acceptance for the yard in this case study is the dimensions of the ship, which is dependent on the size of the quay and slipway areas. Therefore, it is important to decide on size of these areas so that maximum ship length can be defined.

Before the acquisition of the ship and taking the ship to the yard, approval from the harbour authorities and the environmental agency is required. In order to get the initial approval, a basic Ship Recycling Plan (SRP) should be developed and presented to the relevant agencies. In addition, required documents should be submitted to the Port Authority for the acceptance of the end of life ship.

Once the required document from the ship owner is acquired, a visit to the end of life ship will be scheduled for the survey and to develop an offer according to condition of the ship, overall quality of the equipment and, if available, the amount of hazardous materials on board the ship. At this stage, it will be very useful to gather as much as data about the ship to plan the process. Ship will be surveyed to identify its condition, possible gains, inventory; especially Inventory of Hazardous Materials (IHM). If the IHM is already conducted by a trusted party, the current one will be used. However, the IHM has not been conducted or the source is not reliable, then IHM survey will be organized to plan removal of the hazardous materials.

After the contract with the ship owner, next important step is the transport of the ship to the ship recycling yard. Depending on the contract, end of life ship can be brought to ship recycling yard by the owner or delivery to the yard can be yard's responsibility. Ships are sold generally on the "as is where is" concept in which the transport of the ship to the facility is the responsibility of the buyer or end of life ship can delivered to the buyer at the anchorage of the facility (Puthucherril, 2010b). Once the ship is transported to the yard, it will be docked to quay area and prepared for the next steps.

Preparation of the ship

After the docking, preparation of the ship for the recycling step will start. In this step, inventory of the ship will be prepared for the IHM and equipment, ship recycling plan will be prepared, decontamination of the ship from the hazardous materials will be carried out. The process flow of this step is given in the Figure 6.3.

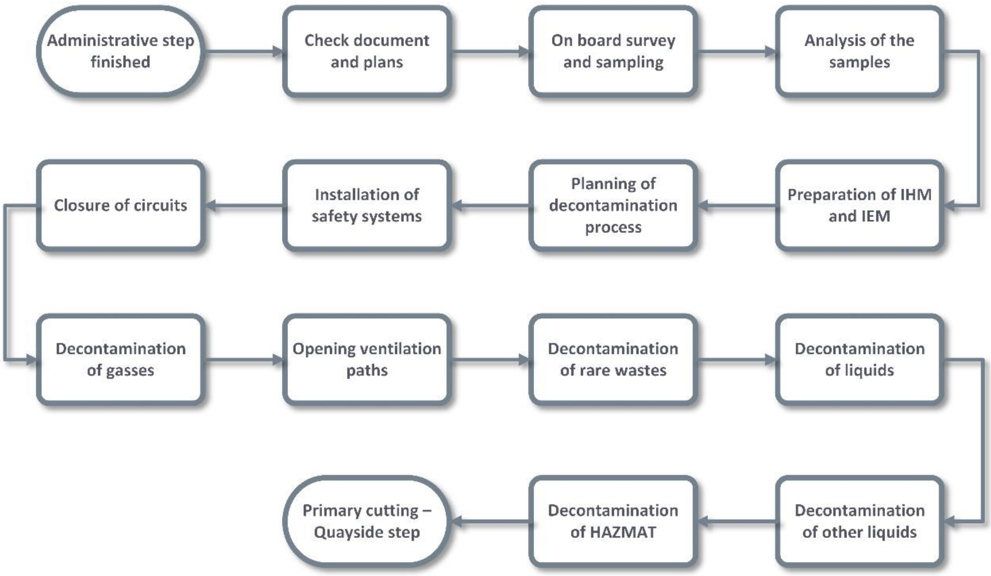


Figure 6.3: Process flow for the preparation of the ship step of ship recycling

The first step of this stage will be checking the documents and plans of the ship. Next on board survey is conducted, samples are taken and then the collected samples (if suspicious) sent to analysis for further testing. Following this, IHM and inventory of equipment and material on board the end of life ship are prepared. In this yard, a professional team will conduct the preparation of the IHM step even if the ship-owner presented the IHM (unless it was conducted by very reliable IHM expert). Also during the IHM survey, inventory of the equipment and materials on board will also be prepared. These two inventories will greatly increase the knowledge on the ship which will directly contribute to the safe and environment friendly ship recycling.

After the IHM, the ship recycling plan is prepared according to the IHM report and any other documentation (such as general arrangement plan). IHM is essential on this point for occupational and environment friendly ship recycling as it will be possible to know where the hazmat is located and what the quantity is. Following the preparation of the ship recycling plan, the ship is decontaminated. Hazardous materials on board the ship are removed according to the IHM and ship recycling plans while the ship is on the quay. Decontamination is first planned in detailed and then next steps, the installation of safety measures for workers and environment and closure of (e.g. electrical circuits, pneumatic, and hydraulic), are followed.

Once these safety precautions are taken, inspection is carried out to make sure compartments are gas-free. The liquid waste; the fuel-oil, diesel, waste oils, sludge and oily water are then removed from the ship. Depending on the condition of the liquid waste above, it will either be sold if it is usable, or it will be treated in the yard’s liquid waste treatment units if it is not usable. Subsequently, ballast water and other fluids are removed. In addition, the hazardous materials listed in the Part I of the IHM, Asbestos, PCB, TBT and ODS will be also removed by an external team of experts during the decontamination stage of the ship. After the decontamination, primary cutting of the ship will start on the quay

Primary Cutting-Quayside

In this stage, primary cutting of the superstructure of the end of life vessel will be conducted. The general approach for the ships will be to start cutting from the top of the structure and continues downwards towards the keel. Before entering or working in any closed space, detailed analysis of the environment will be conducted (measurement of atmospheric conditions) for occupational health and safety. Also further safety precautions will be taken in the working area before commencing the work. Then general cleaning of the vessel is done; the extraction of the reusable equipment with means of easy access and the cutting of upper deck structures. During the cutting of the structures, any structural or outfit element including pipes, cables, wiring etc will be cut and removed from the ship. Before hot cutting, if the analysis conducted in the previous step show that paint of the area contains toxic material or heavy metals above legal limit, pre-treatment with sand grid will be conducted. In addition, the areas that potentially contains hazardous materials are isolated to prevent any contamination to the air or other parts of the ship. Hazardous material in the isolated area will be removed and taken to the warehouse to be treated (Figure 6.4).

Figure 6.4: Process flow for the primary cutting on quayside step of ship recycling

Cutting and extraction steps continue until the work reaches machinery room. During cutting works, the ship will be still afloat. Hence, it is important to keep the ship levelled. Therefore, during this step continuous stability calculations will be conducted by the yard. Extracted materials (steel, non-ferrous metals, wood, plastics, etc.) and equipment will be separated and managed on the land after transferred to the area.

When the engine room is reached, equipment in the engine room will be the removed. Remaining liquids and hazardous wastes is removed (if left any) and extraction and ventilation path is opened. Before starting dismantling the equipment, it is important to disconnect the pipes, wiring and mechanical connections. After cutting/dismantling the connections, equipment are dismantled from the fixing points and taken to the shore with the crane. After removing the equipment from the ship, next step is transferring the ship to the second primary breaking area; ramp of the yard.

Transfer to the ramp and Primary cutting - Ramp

After the operations in the quay, hull will be transferred to the ramp with the help of the tugs and the chain pullers. Hull will be put in position from the quay to the ramp with the help of the tugs. Once the hull is positioned in-line with the ramp, chain pullers, located at the end of the ramp, are attached to the ship's anchor. Chain pullers and tugs (pushes the ship up towards the ramp) will position the ship as far as possible up the ramp. Once the ship is positioned, hull will be fixed and secured to the ramp (Figure 6.5).

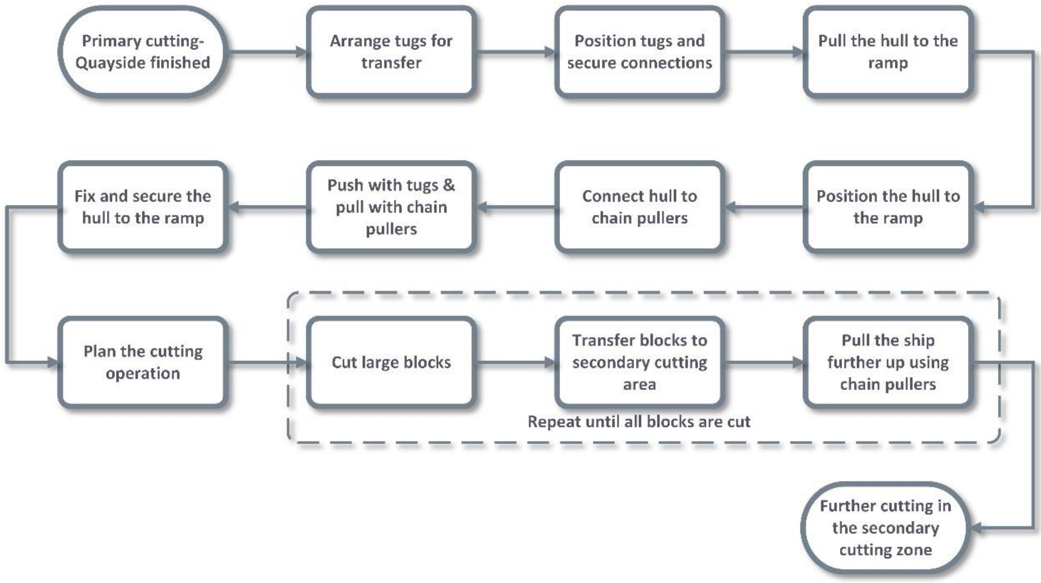


Figure 6.5: Process flow of the transfer to the ramp and primary cutting on the ramp

Cutting, separation and transfer to tertiary cutting area:

Once the ship is secured, the further cutting can be done on the ramp. The important issue on this step is always cutting above sea level. Large blocks will be cut from the hull using shear cutters, oxy-fuel cutters and other methods and the cut block will be anchored and fixed to the crane and travelled to the secondary cutting zone. As the working area gets close to the cutting area, the hull will be pulled further using the chain pullers.

Secondary cutting zone:

Once the blocks are cut on the previous stage of the dismantling, these blocks will be transferred to the secondary cutting zone for further dismantling (Figure 6.6). The main purpose in this step is to cut the steel for smaller pieces to facilitate easier transport to the steel mills. Similar to the previous step, shear cutters, oxy-fuel cutters and other methods will be used.

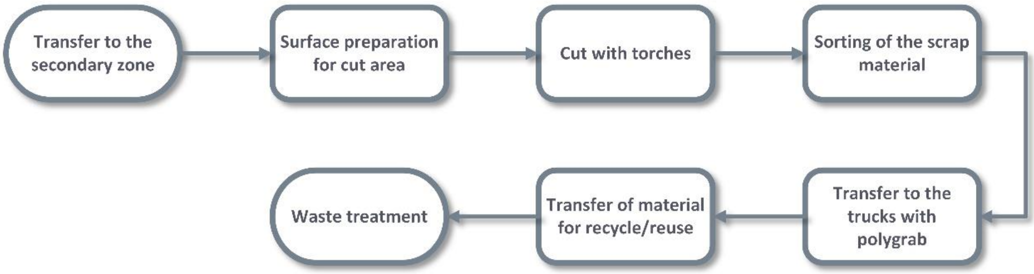


Figure 6.6: Process flow in the secondary cutting zone

During cutting operations separation of metal and other non- hazardous materials are done as well as classification and storage of waste removed from the primary cutting in the quay. Classification of scrap metals as steel and non-ferrous. Also, all waste, materials and equipment will be placed separately and prepared for further processing and treatment.

Treatment of fluids & residues:

In this process, waste which was removed from the ship in the previous stages of the dismantling will treated. There are several stages of this process that changes according to the type of the waste. The process will always be carried out under strict environmental control. The treatment of the waste will not be investigated as part of this study. The overall simplified flow of the process is given in Figure 6.7.

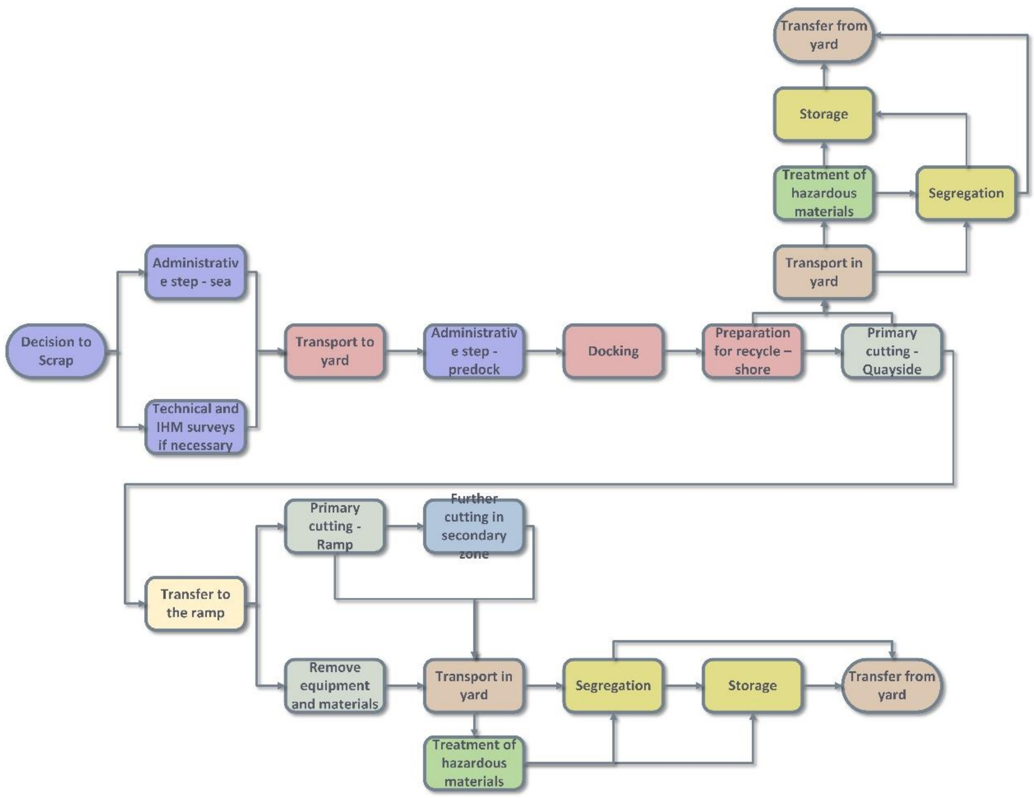


Figure 6.7: Simplified flow of the process foreseen in the yard

According to the process diagram, the required facilities for the ship recycling yard is listed together with activities in these facilities as given in Table 6.1.

Table 6.1: Facilities that are required in the yard and activities in these facilities

Facilities	**Activities**
Quay	IHM Preparation Detailed SRP Decontamination Removal of equipment, machinery and furniture Primary cutting and removal of superstructure
Ramp	Primary cutting of blocks
Crane	Transfer from the primary zone to secondary zone/segregation area
Chain puller	Transfer from quay to ramp
Offices	Administrative works
Secondary cutting zone	Further dismantling of blocks
Segregation zone for non-hazardous materials	Non-hazardous material segregation
Storage zone for non-hazardous materials	Storage for different materials; steel, rare metals, machinery, other materials etc.

Facilities	Activities
Waste treatment facility	Treatment for the solid and liquid waste from the ship
Hazardous material storage	Storage for hazardous material that will be treated externally
Emergency response facility	First aid and other response in case of emergency
Loading Zone	Loading of materials
Equipment storage	Storage for the equipment that are used during daily tasks
Entrance	Entrance of the yard
Workshop	Closed area for small dismantling operations

Waste treatment facility includes the following installations

- Water, Fuel and Oil Tanks
- Sludge and Contaminated oil Treatment Facility
- Ballast Water and Process/lixiviate water Treatment Facility
- Asbestos Handling Installation.
- Sorting of Non-Hazardous Solid Waste Installation.
- Solid Waste Deposits.

After defining the process range and overall characteristics of the yard design, next step is the analysis of the physical environment of the yard. Even though there was no site survey conducted as part of this thesis a data collection study was conducted on the location of the yard. Yard location is very close to road and industrial zones. Also, yard area is not in the proximity any residential area therefore wind direction is not a problem. Geotechnical data analysis was not conducted as part of this thesis but the assumption is, it is suitable for the purpose. Overall dimensions of the yard is given in the Figure 6.8.

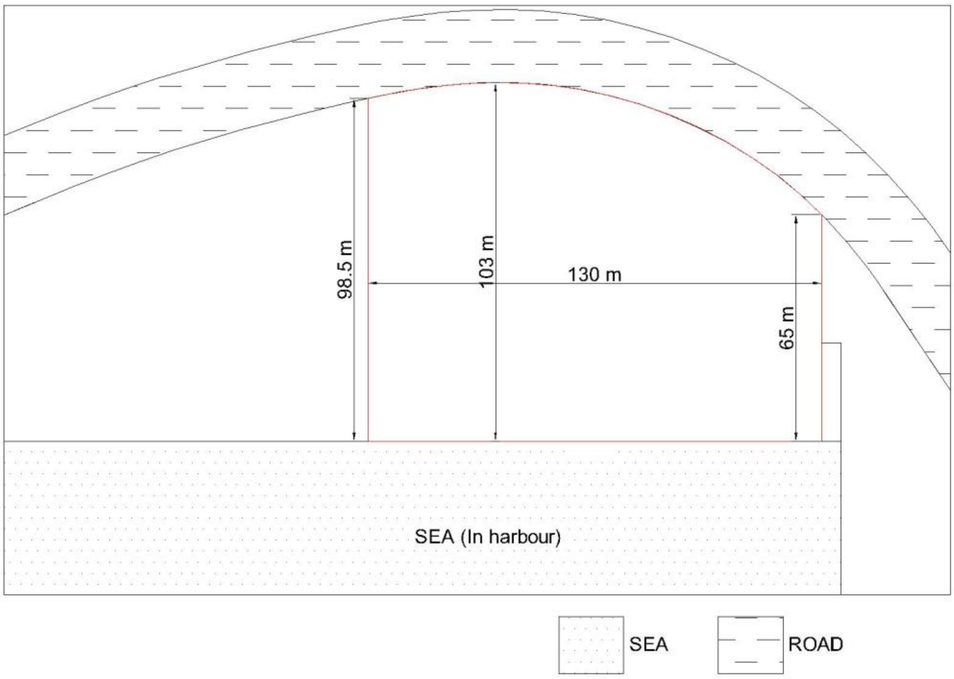


Figure 6.8: Overall area of the yard

The overall length of the yard is approximately 130 meters, the width of the yard is 98.5 metres and approximate area of the yard is around 12800m^2. The overall size of the yard and the requirements of the chain puller are the criteria which limit the ramp (slipway) size (to around 90 meters). The yard can safely dismantle ships up to 190 meters (considering the limitations of the slipway and the requirement of local authorities). Another important criterion for the yard is the size of the blocks cut from the ship which is mainly dependent on the crane capacity. Yard aims to purchase a 900 tonne-meter crane (15 tons capacity at 60 metres and 60 tons lifting capacity at 15 meters), which should be enough for the yard's requirements as common practice for the weight of blocks is around 10-15 tonnes. Overall, yard aims to employ minimum of 12 people consisting of one manager, one administrative person, six workers, one technical supervisor, one machine operator and two personnel responsible for waste treatment. To sum up

- 900 tonne-meter crane
- One polygrab for transfer and loading in the yard
- Forklifts and trucks for material transfer in the yard

- 12 personnel
- Trucks for the transfer of materials out of the yard

After deciding the approximate resource numbers and capacities, system analysis step of the framework can be finalised. As suggested in section 5.3.1.2, following data collected following the requirement analysis and system analysis;

- Target ships for recycling
- Desired annual recycling capacity
- Physical constraints of the yard
- Approximate resource numbers and capacities
- Major facilities required
- Production processes and methods

6.2.2 Primary Design and Analysis Phase

6.2.2.1 Primary Layout Design

Following defining the ship recycling design criteria, basic layout design step can start. In this step following sub processes will be covered;

- Material flow analysis
- Activity analysis and space allocation
- Draft layout, Modification and Generation of alternative designs

6.2.2.1.1 Material flow analysis

In order to calculate the rest of the areas, some assumptions need to be made on the material flow and the material composition of the ship. In order to make an accurate assumption, studies investigating the material flow from end of life ships were reviewed (Adak, 2013, Andersen et al., 2001, Andersen et al., 1999, Demaria, 2010, Hess et al., 2001, Sarraf et al., 2010, Sujauddin et al., 2015a, Jain et al., 2016). Jain’s (2016) study is the most detailed and demonstrates the complete material composition of an 11000 LDT of a handymax bulk carrier (Jain et al., 2016). Since 11000 LDT handymax ship is also fits to the maximum size for the yard's capacity in terms of length, it is suitable to use the material composition for the yard's design

Authors divided the weight groups of the ship into nine different categories (Jain et al., 2016):

- W01 Ferrous scrap
- W02 Non-ferrous scrap
- W03 Machinery
- W04 Electrical and electronic equipment
- W05 Minerals
- W06 Plastics
- W07 Liquids, Chemicals and Gases (Excluded from the initial analysis as it is not part of LDT but then included
- W08 Joinery
- W09 Miscellaneous

Using the documentation on-board the ship (stability booklet) to estimate the weight groups in the case study ship. Then, Jain included the weight of liquids, chemicals and gasses through a correction. Calculation of the different weight groups is given in Table 6.2.

Table 6.2: Material stream, quantity and weight distribution (Jain et al., 2016, Jain, 2017)

Code	Material Stream	Quantity (% of LDT)	Weight (t)
W01	Ferrous scrap	84.60	9343.22
W02	Non-ferrous scrap	1.04	114.86
W03	Machinery	6.18	682.52
W04	Electrical and electronic equipment	1.24	136.95
W05	Minerals	2.52	278.31
W06	Plastics	1.19	131.42
W07	Liquids, chemicals and gasses	1.03	113.75
W08	Joinery	1.28	141.36
W09	Miscellaneous	0.92	101.60
TOTAL		**100**	**11044**

Jain et al. also investigated the material flow further and categorized the materials into two major streams, economic value stream and non-economic value stream Jain et al. (2016). Jain defines economic value stream as the products that can be sold for reuse/recycling (hence creating income) and non economic value stream involves the products that needs to be treated or needs to be sent to landfill. Jain mapped the flow for a generic yard, and this distribution was modified to design the zones and storages for this case study. Modified distribution of the flow according to the zones and storages are shown in Figure 6.9, however, the amount of the material that goes through the segregation zone is not included in order to simplify the diagram. In order to detail the design of the non-hazmat storage, segregation zone, and secondary dismantling zone some assumptions need to be made.

It is important to accurately model the material flow and collect data in a reliable way. In order to run the framework and associated simulations. However, in a conceptual yard this information is not available yet. In such cases this data needs to be predicted as accurate as possible. Therefore, material flow information provided by Jain (2017) will be investigated and used for this purpose in this study. The particulars of this ship is given below (Jain et al., 2016):

- Length overall: 190.00 m
- Length between perpendiculars 183.05 m
- Breadth moulded: 32.30 m
- Depth moulded to upper deck: 17.50 m
- Design draft: 11.10 m
- Deadweight: 12.00 m
- Cargo capacity: 44500 t

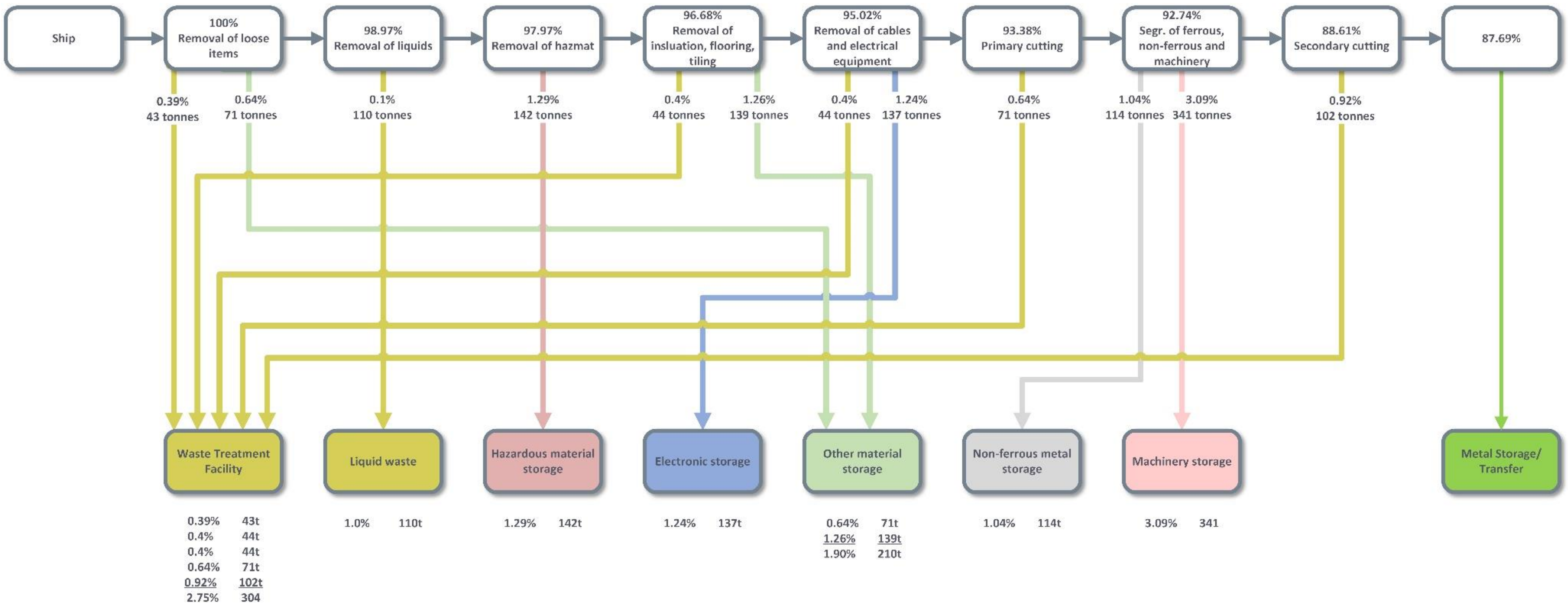


Figure 6.9: Ship recycling process of the case ship showing the quantities of material flow to zones and storages in terms of percentage of LDT and tonnage (Modified from Jain (2017))

Material flow and assumptions are summarized below (Modified from Jain (2017)), also detailed diagram is shown in Figure 6.10;

In the following table, material flow has been summarized in detail. The material flow shown in Table 6.3 will also be helpful on the design of the storages.

Table 6.3: Total material flow according to the area/facility (created using Jain (2017))

Area/Facility	**Total Material Flow**
Waste Treatment Facility	2.75% of LDT (304 tonnes)
Liquid Waste Treatment	0.1% of LDT (110 tonnes)
Hazardous Material Storage	1.29% of LDT (142 tonnes)
Other Material Storage	1.90% of LDT (210 tonnes)
Electronic Storage	1.24% of LDT (137 tonnes)
Non-ferrous metal storage	1.04% of LDT (114 tonnes)
Machinery storage	3.09% of LDT (341 tonnes)
Metal storage	6.58% of LDT (751.5 tonnes)
Steel mill	81.10% of LDT (9271 tonnes)
Segregation Zone	6.89% of LDT (2541 tonnes)
Workshop	5.07% of LDT (576.7tonnes)

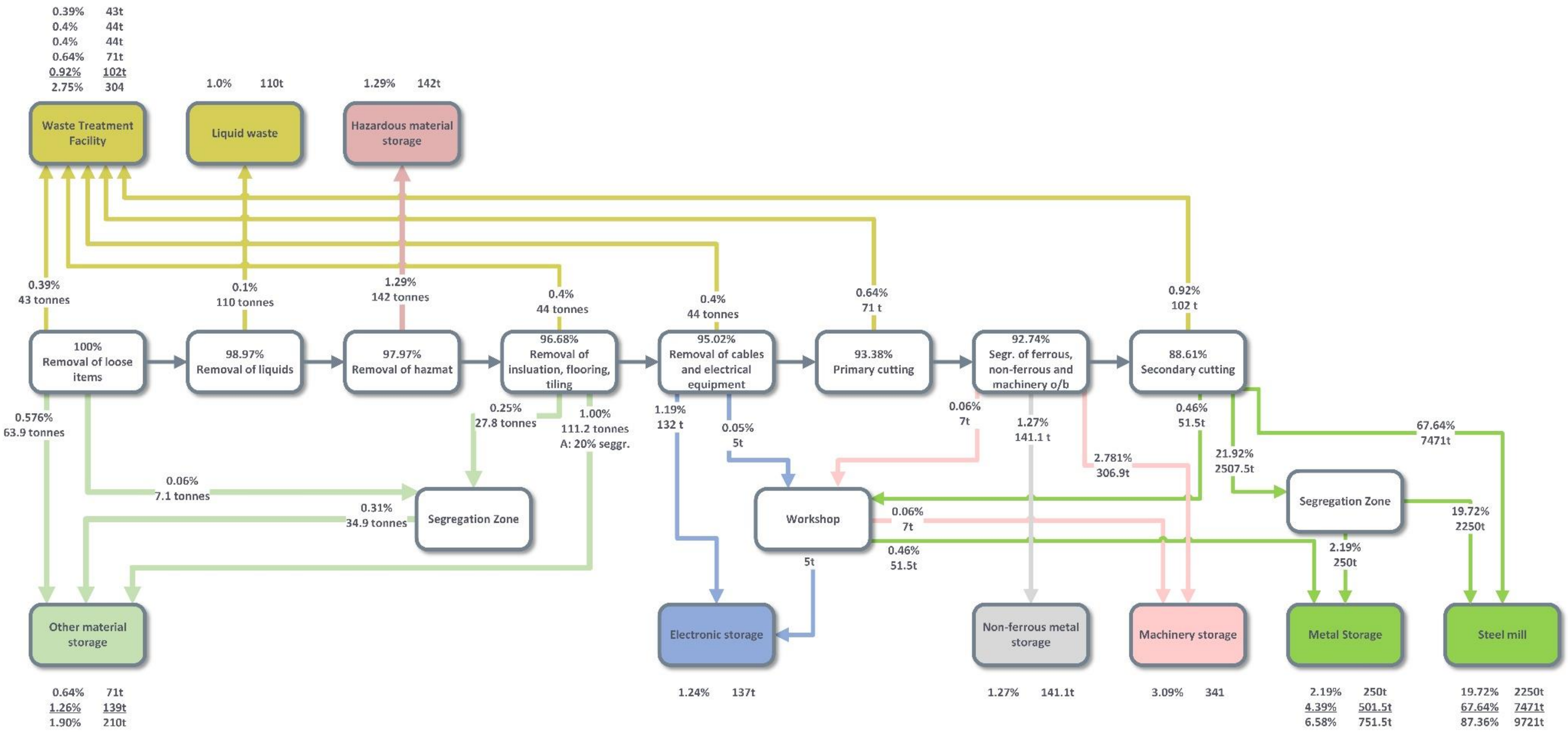


Figure 6.10: Corrected material flow to zones and storages in terms of percentage of LDT and tonnage (Modified from Jain (2017))

6.2.2.1.2 Activity relationship analysis and space allocation

This step conducts activity relationship analysis to create the activity relationship chart. Following this, the relationship chart will be transformed into an activity relationship diagram.

In order to conduct the activity relationship analysis a brainstorming activity with two experts on ship recycling industry was conducted and the closeness of the facilities are ranked. One of the experts is chosen from the industry (with more than 10 years of experience on ship recycling), and other expert is chosen from the academia (5+ years of experience on ship recycling). Each participant in the activity were asked to fill this form separately, and following this each rating were discussed to make a final decision. The final version of the activity relationship chart for the ship recycling yard is shown in Figure 6.11.

Following scale was used in the ranking;

- A Absolutely necessary;
- E Especially important;
- I Important;
- O Ordinary
- U Unimportant;
- X Not desirable.

Reasons in the relationship ratings are demonstrated in Table 6.4.

Table 6.4: Reasons for relationship ratings

1. Flow of materials	7. Frequency of contact
2. Need for personal contact	8. Urgency of service
3. Use same equipment	9. Cost of utility distribution
4. Use common records	10. Use same utilities
5. Share same personnel	11. Degree of communicative or paperwork contact
6. Supervision or control	12. Specific management desires or personal convenience

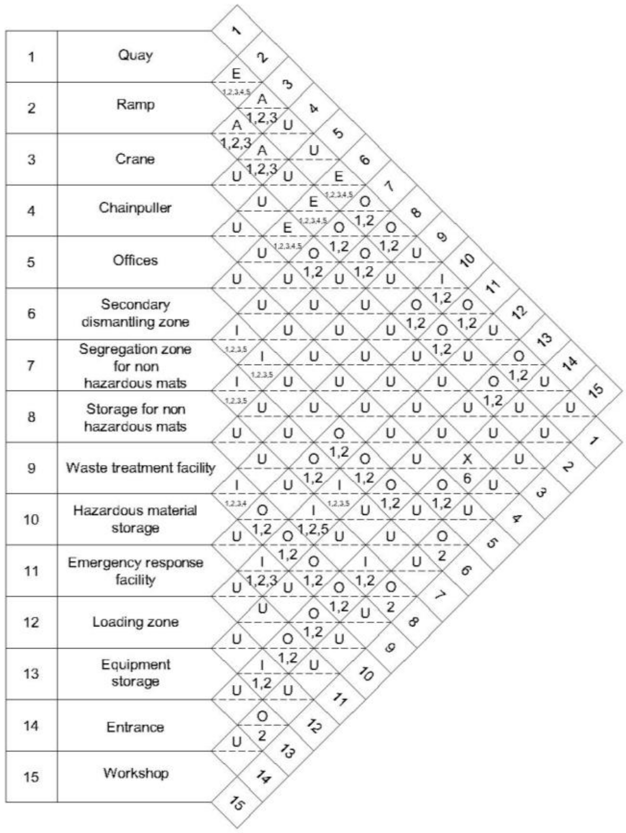


Figure 6.11: Activity relationship chart for the yard

The findings of the activity relationship analysis are summarised below:

- Crane in the yard will handle all material transfer from quay to other zones and from ramp to other zones. Therefore, it is "Absolutely necessary" for crane to be close to the ramp and the quay to increase the benefit from the crane.
- Chainpuller will be used to transfer the ship to the ramp, therefore, it should be placed at the end of the ramp.
- Activities in the quay, ramp and secondary dismantling zone follow each other. Therefore, it is "Especially" important for these two facilities to be close to each other.
- Segregation zone and secondary cutting zone also has consecutive activities and significant amount of material flows from secondary zone to segregation zone. Therefore, it is "important" to keep these facilities close to each other. Similarly, segregation zone should also be close to

storage areas to minimise the transportation in these zones. These areas should be close to the loading zone of the yard to minimise the traffic and distance between these zones. Moreover, loading zone should be close to the entrance of the yard to keep the traffic due to the trucks in the yard at minimum level.

- In order to keep the exposure to hazardous wastes, it is important to keep the waste treatment facility, quay and hazardous material storage close to each other.

After completing the chart, next step is transforming the relation to a diagram so that the rough layout can be created. Manual or CAD based approach can be adapted transform the chart to a diagram. First, a rough draft was created by using the information collected in the activity relationship diagram. (Figure 6.12).

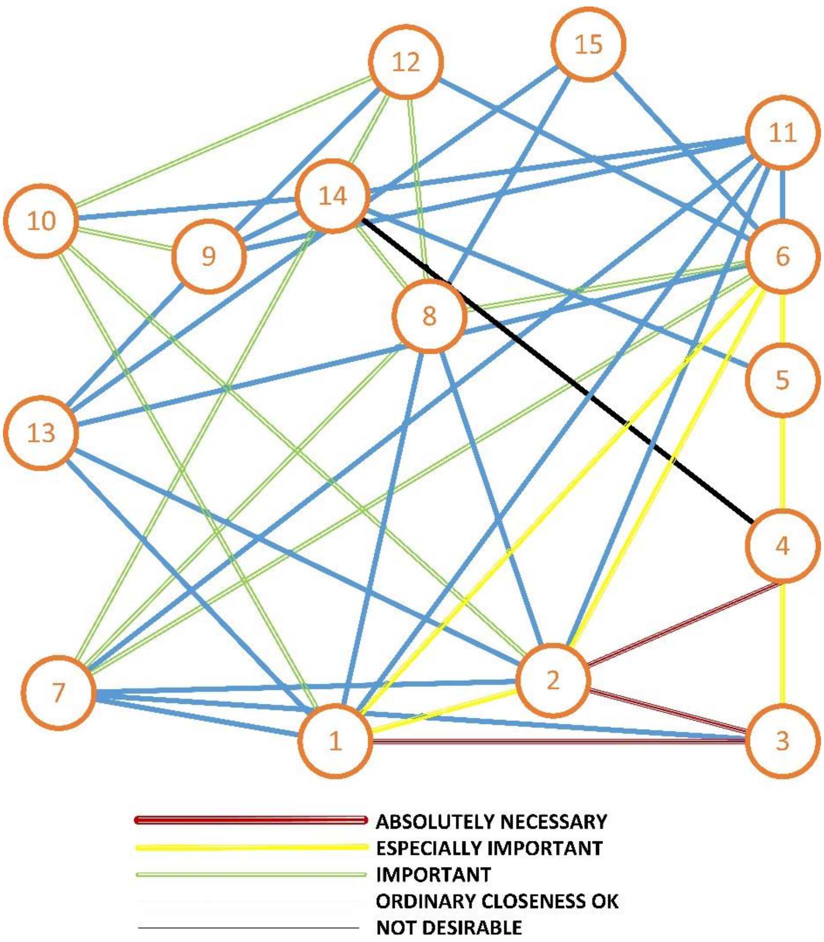


Figure 6.12: First created diagram

Using the activity relationship chart, all the facilities should be connected to each other using the associated line with the rating. Next, the first diagram created, should be modified to fit the area where the yard will be located to. For this case study, quay, ramp, crane and entrance of the yard should be placed in their primary location. Then other facilities should be placed according to their relation with these four facilities. Also, lines can be re organised to demonstrate a clearer picture.

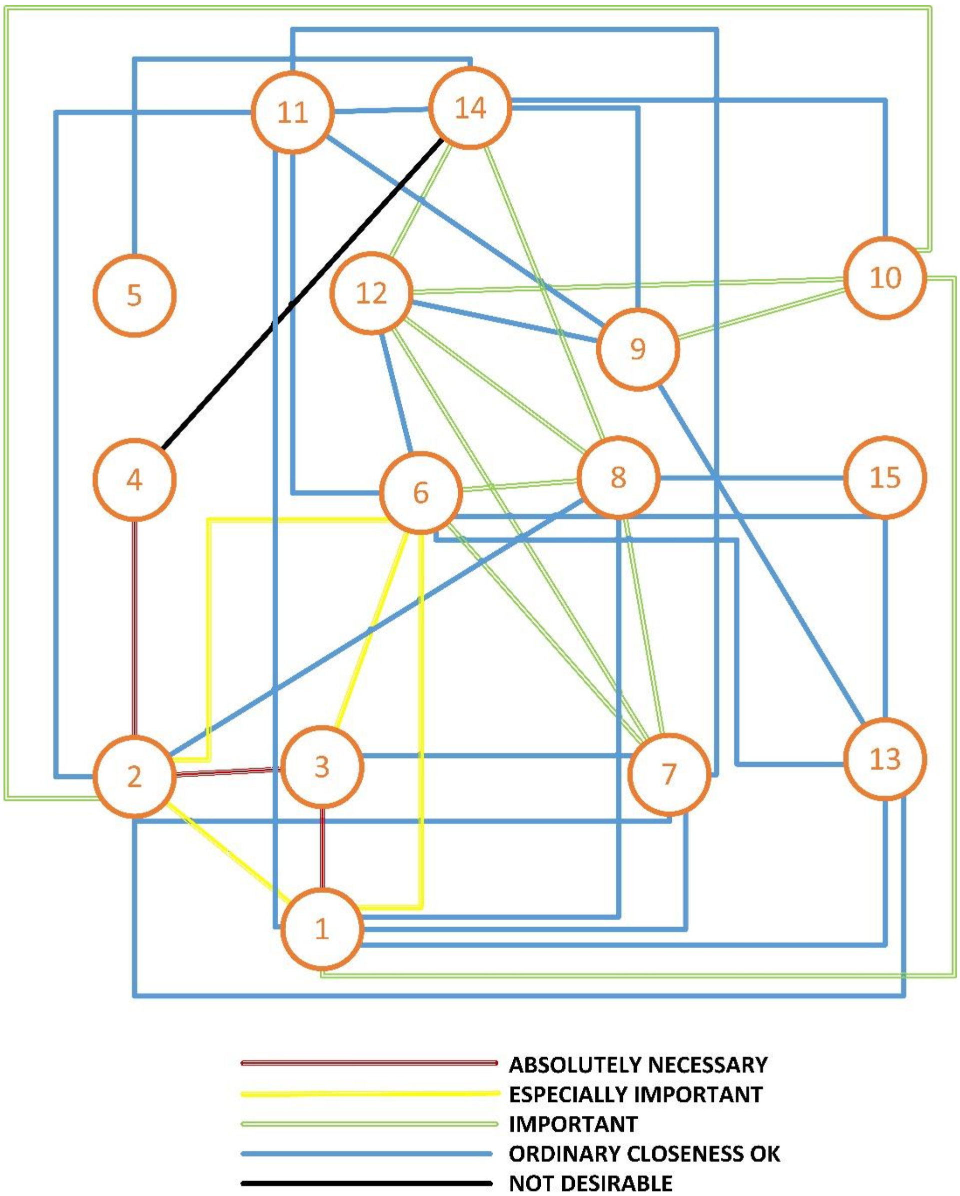


Figure 6.13: Redrawn diagram for better fit to the area (considering the entrance and the quay) as well as for best fit of all relationships

These initial drawings were then moved to AutoCAD to accommodate more accurate drawing and to integrate the space requirement with the activity relationship diagram.

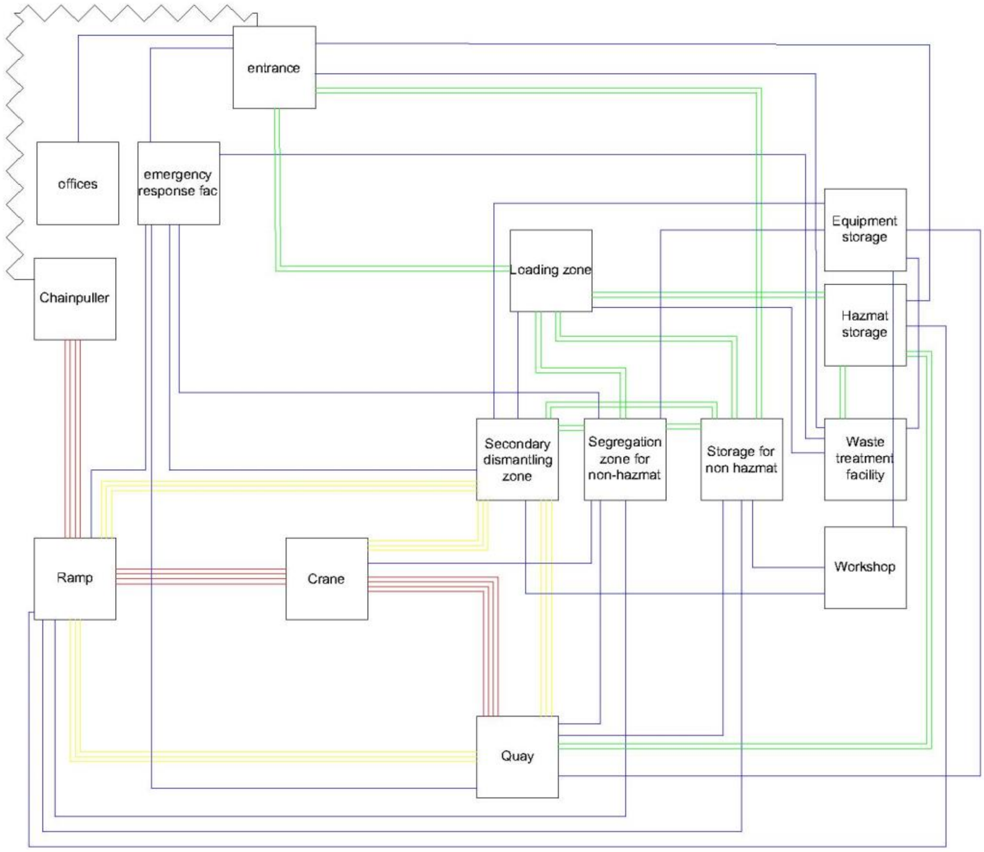


Figure 6.14: Reorganized drawing in AutoCAD

The next step is the allocation of the areas. Area of each facility will be investigated separately and the methods to decide on the initial area will be summarised next.

6.2.2.1.2.1 Quay Area and Slipway

Quay area is usually prebuilt areas in the harbours. Important part with the design of quay area is the length and the depth. In this project, quay area is prebuilt in the area and it is 800 m^2 and the quay has a length of 130m and 10 meters width (quay is in total 220 m exceeding the yard's boundary).

Length of the ramp will be 85 meters, (considering that the overall length of the yard is 98 meters and chain puller and the necessary equipment is 10 meters long). Ships up to 190 meters were investigated through known databases (fleetmon, 2018, vesselfinder, 2018) and it is determined that these vessels' beam may go up to 30 m wide. Considering the target ships of the yard, the dimensions of the slipway is determined as 85 meters in length and 30 meters in width. (Other aspects of the slipway, such as the structural requirements, angle, surface and traction, will not be investigated as part of this study. Literature can be studied for these details: Mackie (2018) and Eyres and Bruce (2012)).

6.2.2.1.2.2 Chainpuller Area

Next step after the slipway is the area allocation of the chainpullers. The overall dimension of a single chain puller is approximately 6 meters in length and 1.5 meters in width, there will be two chainpullers placed in the yard and with the connections and other equipment, 10 meters on the slipway direction. Since the chain pullers need to be placed on each side of the slipway, width of the chainpuller facility should also be same with the slipway width. Therefore, dimension of the chainpuller facility will be 30 meters by 10 meters. Following the slipway, crane area is decided through the manufacturer specifications, which is approximately 10 meters by 10 meters (liebherr.com, 2018).

6.2.2.1.2.3 Storage for non-hazmat

Storage for non hazardous materials will include storage of following material types;

- Metal storage (Ferrous steel storage)
- Non-ferrous metal storage
- Electronic storage
- Liquid storage
- Machinery storage and
- Other materials storage

Considering the fact that it takes around 2-3 months to dismantle 10,000LDT ship (Hiremath et al., 2015), the storage zones does not need to be designed to store all the material from ship. The materials stored in these zones will be periodically transferred out of the yard. Therefore, it is not necessary to store the whole amount of material shown in Table 6.3; the amount that will be taken into account during the yard design is shown in Table 6.5. These numbers were generated through the daily production rate which is estimated by the yard.

Table 6.5: Area/facility in the yard and total material flow

Area/Facility	**Total Material Flow**	**Planned Capacity**	**Area required**
Metal storage	751.5 tonnes	60 tonnes	30 m^2
Non-ferrous metal storage	114 tonnes	30 tonnes	60 m^2
Electronic Storage	137 tonnes	20 tonnes	25 m
Machinery storage	341 tonnes	100 tonnes	150 m^2
Other Material Storage	210 tonnes	50 tonnes	150 m^2
Total area			415 m^2

The calculations for required area was done on the basis of the items. For example for the metal storage, the following assumptions was done

- Yard will cut the plates in secondary dismantling zone to smaller pieces (initial plan is 1 meters by 0.5 meters) and stack the plates (that will not be sold directly) together. Each stack will be around 2.5 tons minimum.
- Each stack will have 0.5 meter gap for the circulation and loading.

Following these assumptions, sketch in Figure 6.15 was drawn to estimate the area required for storage.

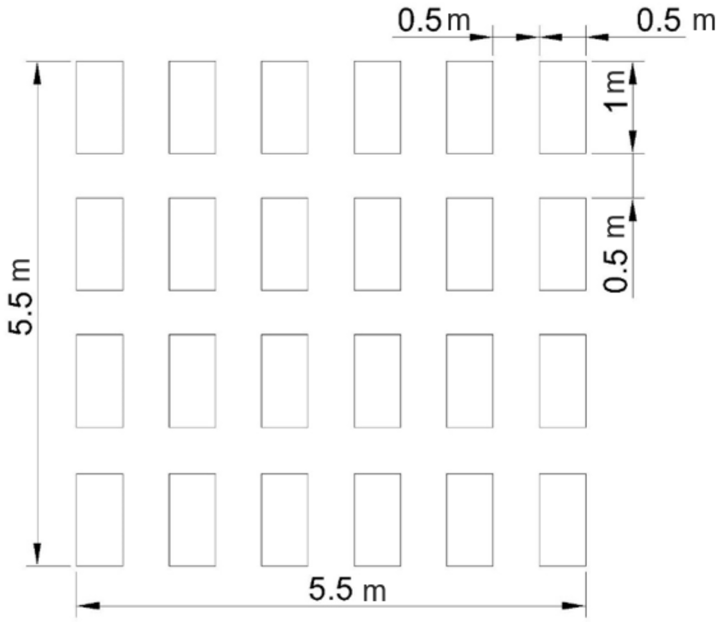


Figure 6.15: Sketch for the allocation of steel plate stacks

Same approach was followed for non-ferrous metal storage, electronic storage and other material storage. On the machinery storage, the average size and weight of main engine, generators and other auxiliaries was taken into account to make the estimation. These machinery will not be stored for a long period, therefore, storage for one ship is considered adequate. Following these calculations, the area for the non-hazardous material storage was decided as 420 m^2.

6.2.2.1.2.4 Secondary dismantling zone

For the design of the secondary dismantling zone, average block size that will be transferred from the primary cutting zone was taken into account. As an average, block with 5 metres by 5 metres dimensions was chosen. For the safety and circulation of carriers within the area, 5 metres gap between the blocks was left. Considering the remaining area on the yard and the performance of the primary cutting zone (the average block transfer from primary cutting zone varies between 20 minutes to hour), capacity of the secondary cutting zone is initially planned for 25 blocks to be stored at the same time. The number of blocks and the gap between the blocks will be considered and modified during the simulation analysis.

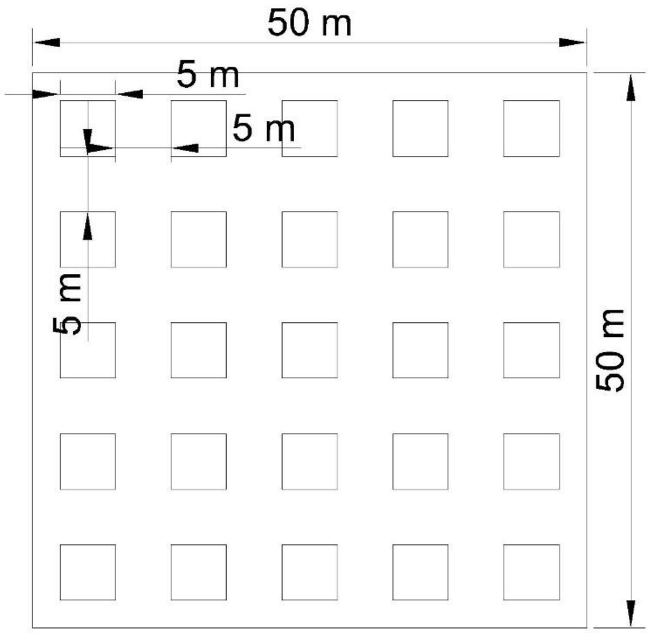


Figure 6.16: Secondary dismantling zone block distribution

6.2.2.1.2.5 Segregation zone for non-hazmat

Segregation zone is the area where the materials are segregated and directed to the relevant area according to the material type. In total, 2541 tones of material (6.89% of total LDT) (Table 6.3) will be stored in the segregation zone. The area required for this zone were discussed with the yard owner and this zone has been limited with 1,000m^2 to accommodate the material flow and the temporary storage of the materials.

6.2.2.1.2.6 Loading Zone

Loading zone is the zone where trucks manoeuvre in and being loaded using the polygrab. The assumption to be made at this point is that two trucks will go in the yard at maximum as there is only one polygrab to load the trucks. Therefore, area is planned according to these resources and operation. 500 m^2 is allocated for loading zone area considering the number of trucks waiting, the polygrab and the manoeuvre zone of these machineries.

6.2.2.1.2.7 Workshop

In the workshop area, small cutting, segregation, dismantling and repair jobs will be conducted. In the workshop following are planned;

- Storage units (with shelving for pieces recovered).
- Mechanical Workshop for small cutting, segregation, dismantling and repair operations
- Equipment maintenance area

This facility was discussed with the ship recycling yard owner and a workshop area similar to their existing yard was planned to be included in this yard. Alternatively, systematic layout planning can be applied to this area (known dimensions of equipment, material, workstations etc.) to accurately calculate this zone.

6.2.2.1.2.8 Storage for hazmat and waste Treatment Facility

Areas for these zones were taken from the initial quotation received by the yard owner from the waste management company. Therefore, Waste treatment facility in this yard’s case requires 625m^2 area of which 375m^2 for solid waste treatment and 250m^2 for liquid waste treatment. Alternatively, target ships should be investigated and the amount of wastes from the vessel should be taken into account when designing the waste treatment facility. In this waste treatment facility following units are planned to be placed;

- Installation for Cable+WEEE shredding and treatment
- Containers for miscellaneous residues
- Sorting of Non-Hazardous Solid Waste Installation.
- Solid Waste Deposits.
- Oily water and sludge tank
- Ballast water and gray tank
- Run-off and lixiviate.
- Fuels and diesels tank
- Used oils tank
- Others

6.2.2.1.2.9 Office area and changing rooms

Office area and changing rooms designed as 200m^2 considering the small size of the administration team and the workers. Four different office spaces (5x5) and a changing room is included in the office area.

6.2.2.1.2.10 Emergency response facility

This should be decided on the equipment, number of doctors, bed size and other furniture. In this project, a small infirmary was placed in the yard as emergency response facility due to the low number of personnel and the closeness of the yard to the hospital. One bed, lockers for the supplies and a small office for the staff is included in the facility

Following the space allocation analysis, areas of the each individual zone are given in Table 6.6.

Table 6.6: Areas allocated for each zone

Facility	**Area**
Quay	800 m^2
Ramp	2,550 m^2
Offices and changing rooms	200 m^2
Waste treatment facility	625 m^2
Chain puller and other equipment	300 m^2
Emergency response facility	50 m^2
Crane	100 m^2
Workshop	230 m^2
Storage for non-hazmat	420 m^2
Segregation zone for non-hazmat	1,000 m^2
Secondary dismantling zone	2500 m^2
Loading Zone	500 m^2
Hazmat Storage	100 m^2
Equipment storage	25 m^2

The area allocations (Table 6.6) and activity relationship diagram (Figure 6.14) were then combined to generate the first layout for the yard. In order to achieve this, area of each zone is placed on the activity relationship diagram and drawn to fit the physical constraints of the yard (Figure 6.17).

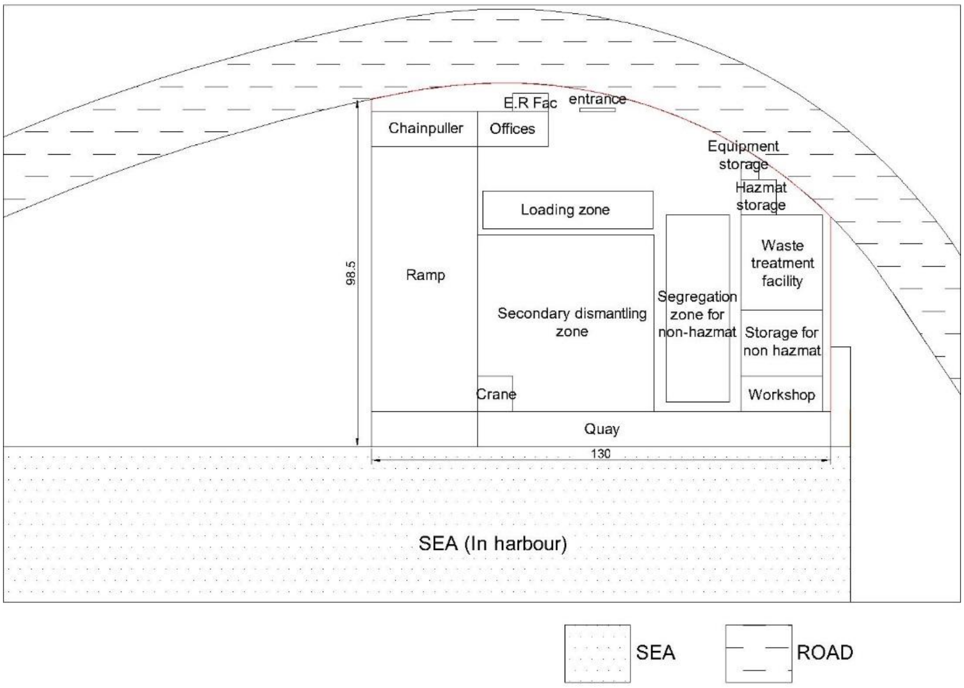


Figure 6.17: Developed layout (alternative 1) for the yard using the methodology introduced and modified version of the layout

The activity relation diagram and the space allocation can be combined in several different ways according to the ratings and the shape of the zones. The systematic layout method places the facilities according to their ranking on the activity relations. It is common practice when applying this layout optimisation designer tries to keep these facilities close to each other. When following this method, several different alternatives can be created depending on the approach. Therefore, several alternatives are created and then evaluated to find the best option based on the expert judgement. In this thesis, It is common practice when applying this layout optimisation designer tries to keep these facilities close to each other. The developed alternatives will be investigated further through the application of simulation.

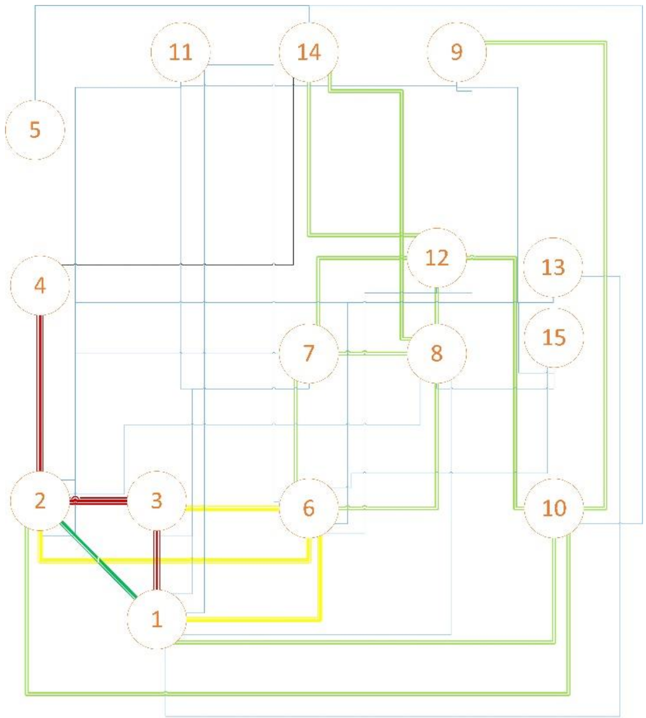


Figure 6.18: Generation of the activity relation diagram for layout alternative two

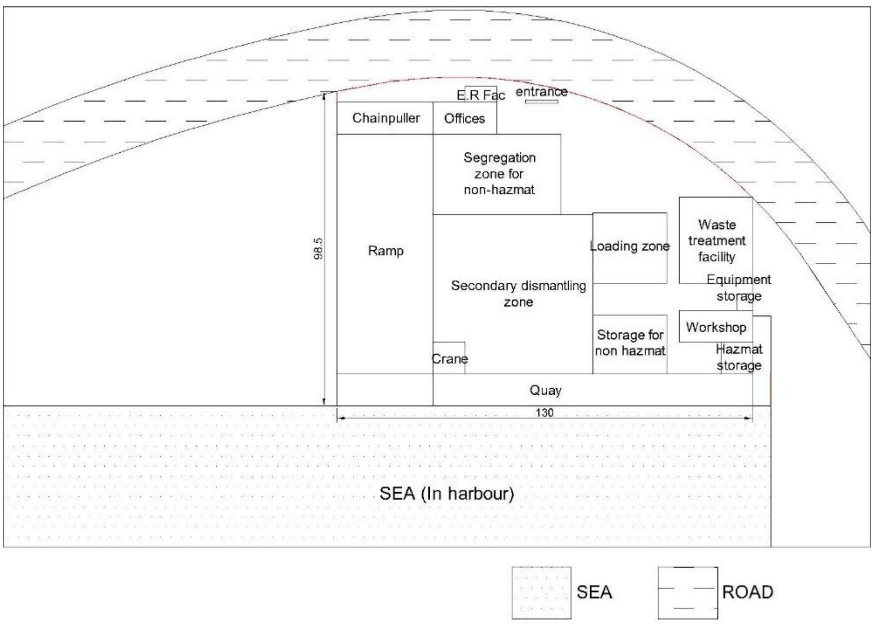


Figure 6.19: Transformation into the layout through CAD

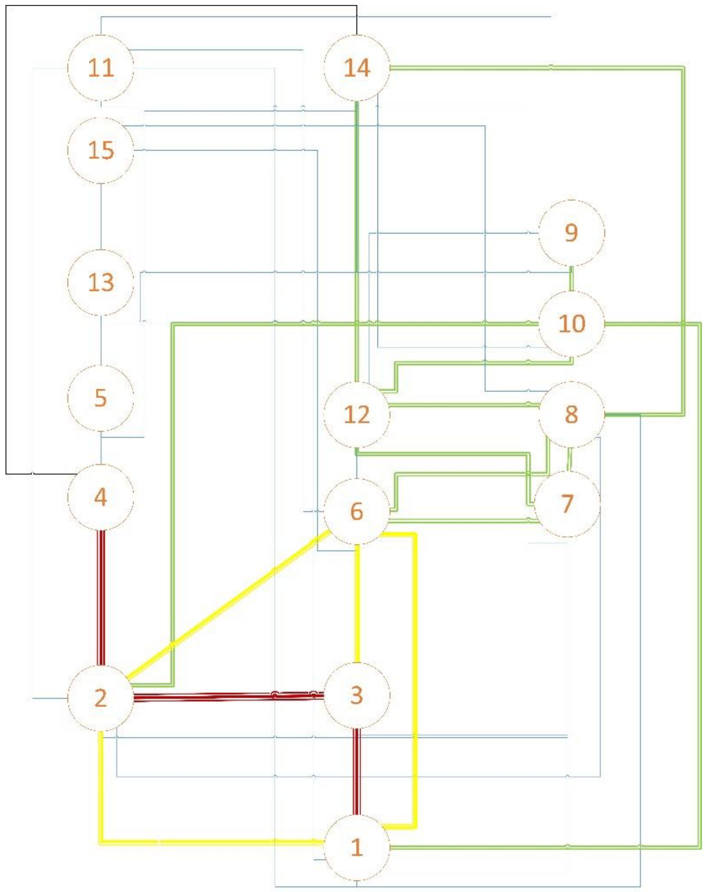


Figure 6.20: Generation of the activity relation diagram for layout alternative three.

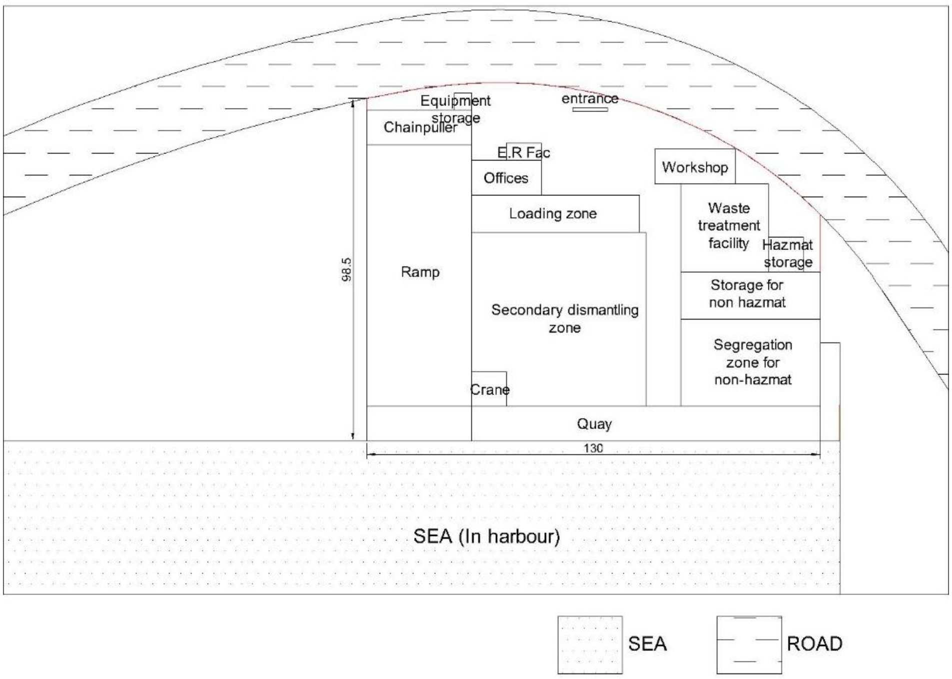
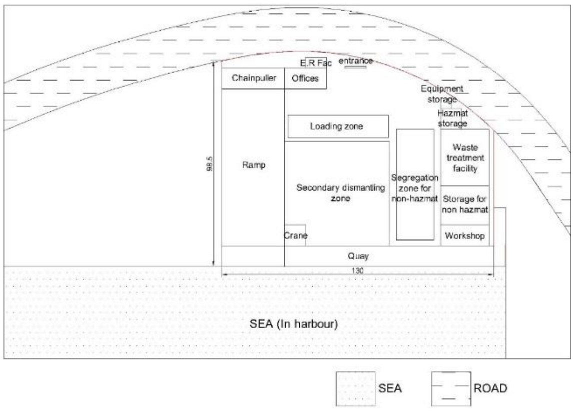
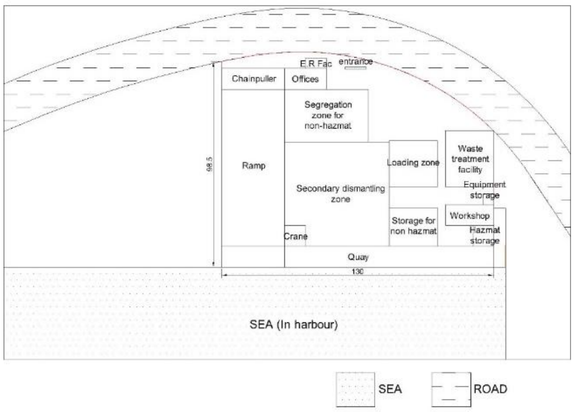


Figure 6.21: Transformation into the layout through CAD for alternative three.

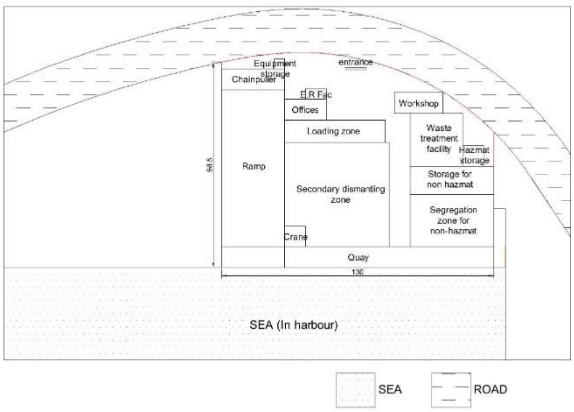
Generation of the alternative layouts for the yard is the last step of the primary layout design. These layouts need to be assessed in terms of performance and economic benefit; therefore, the next step is using the simulation to compare these layouts.



Alternative 1
(Layout 1)



Alternative 2
(Layout 2)



Alternative 3
(Layout 3)

Figure 6.22: Summary of the developed layouts

6.2.2.1.3 Primary Simulation

A generic simulation model for ship recycling industry was introduced in chapter 5 of this thesis. The developed ship recycling model can be quickly amended to a specific case and can be utilised in the analysis of yard designs. Details of the models and modules used are explained further below (the inputs for these modules are given in the Appendix F). First of all, some assumptions are needed to conduct the simulation. These assumptions are summarized below

- All material except steel will be stored in the yard's storage areas.
- All workers have the same production rate, the effect of training and experience is ignored in the simulation.
- Oxy-fuel cutting is accepted to be the only cutting technology (effect of the different technologies is investigated in next chapter)
- The size constraints of the zones should be ignored for all scenarios in at this stage of the simulation (if the area will be kept same).
- The annual working days are accepted as 251 days, therefore, the year-long simulation runs were ceased at 6,024 hours.

In addition to the assumptions, design of experiments for the variables and attributes of the system should be set clearly. Table 6.7 represents the variables identified from Chapter 5, and after consultation with the ship recycling yard, combination of the following factors will be tested throughout the simulation runs.

Table 6.7: Design of experiments for the factors identified previously

Variable name	Level Minimum	Level Maximum	Number of experiments
Worker number	6	96	8
Number of technologies	1	3	3
Secondary cutting zone size	25	77	3
Crane number	1	2	2
Polygrab number	1	2	2
Operator number	1	2	2
Plate size	0.5 x 1 m	1 x 1 m	2
Number of transporters	5	10	2

Focus on primary simulation for the layout planning should be kept limited to the transfer of the entities. The overall process time and the total cost of the operation can be used to compare the performance of the developed layouts. The comparison of these criteria will give the modeller an initial idea on the "better" option. More detailed approach should be followed in the detailed simulation step.

6.2.2.1.4 Model structure and module properties

Ship arrival step

In this step, the ship introduced to the simulation system as an entity. Arrival of the ship is limited to one ship to see the performance of layouts accurately. Similar to the generic ship recycling model introduced in Chapter 4, *Record* and *Assign* modules are logical modules that are used to give properties to the entities and record the arrival time, number ships etc. After this step, ship is transferred to the yard using the Route module.

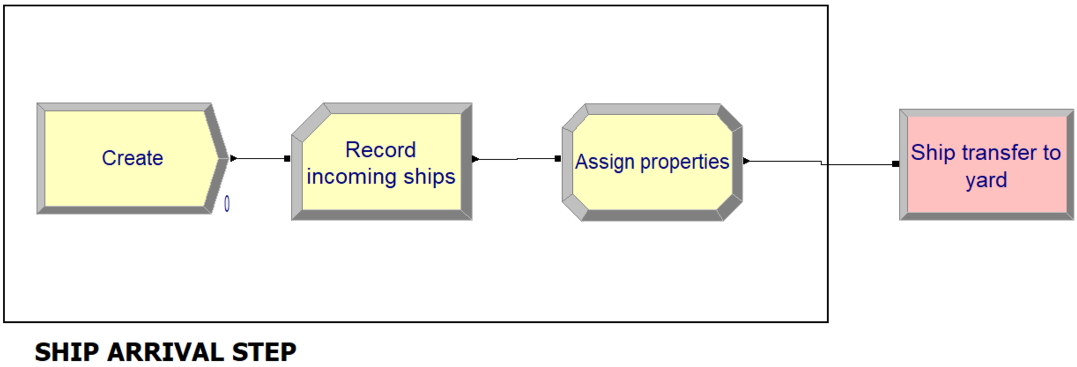


Figure 6.23: Ship arrival step in the model

Docking

Ship arrives at the "Quay" station using the Route module from the previous step. Once the ship enters the Quay station, entity goes through the "Docking of the ship" and "Securing the ship, arranging access and equipment" steps.

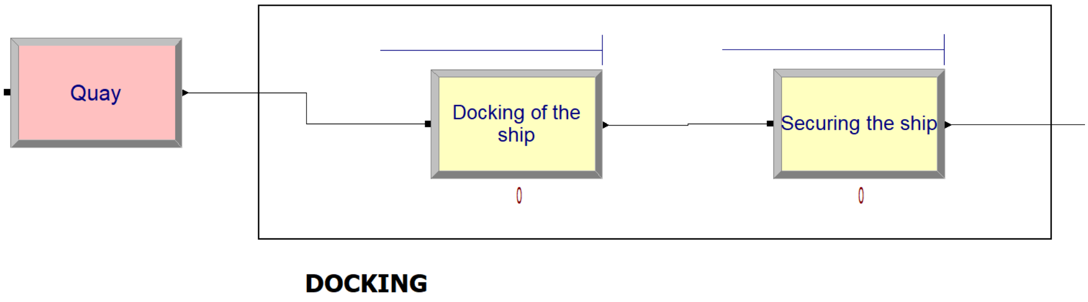


Figure 6.24: Docking step in the model

Preparation for recycle – shore

After the docking, the simulation assesses the requirement for the IHM through the *Decide* module "IHM necessary" (input for IHM requirement is given as 90% as an assumption). If the arriving ship requires an IHM survey, it is conducted through a Delay module as it will be done by an external company. Pre-inspection and safety check follows this module to represent the overall survey and safety check of the ship. "General cleaning of the ship" and "Discharge of fuel and sludge" steps are performed in parallel, therefore, a separate module is used to represent these parallel steps. Following these steps, loose items and liquid wastes are separated from the main flow using the duplicate logic and transferred to the relevant storage units. Yard is planning to use pumps to transfer the fluid waste, therefore, this transfer is represented with a route model as this transfer is not in the scope of the study. Loose items acquired from the ship will be transferred to the storage using the yard's transport equipment, therefore, entities created for loose items goes to material handling section for the transfer (after the assign module for allocation of the material type is run).

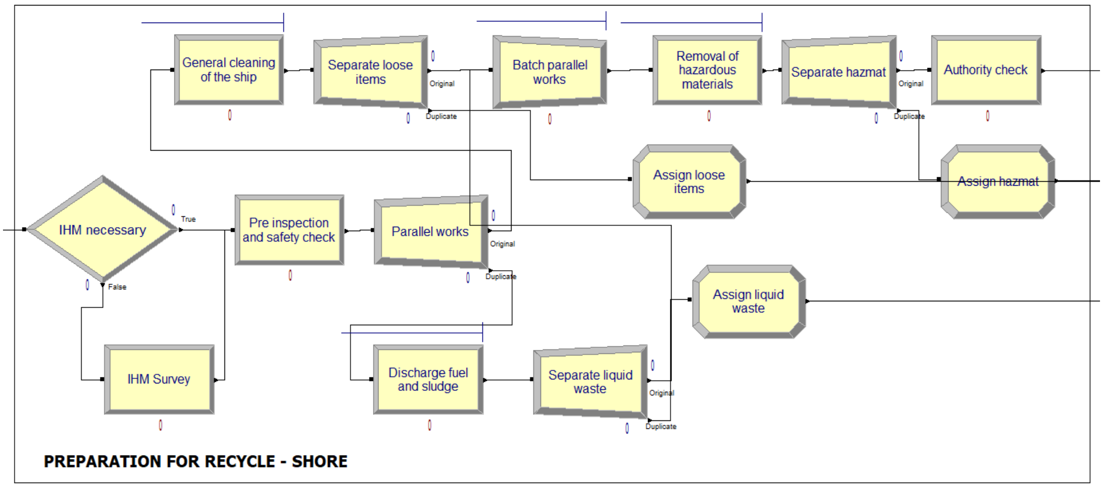


Figure 6.25: Preparation for recycle step in the model

Primary dismantling – quayside

Primary cutting in the quayside uses the logic introduced in the chapter 4 with a minor difference. The model in Chapter 4 was designed for all the block cutting operation to be completed in a single primary dismantling zone. This yard on the other hand requires two separate zones for this operation: quay for the removal of equipment and superstructure dismantling, and ramp for complete dismantling. Therefore, the model has been slightly transformed to address this operational need (Figure 6.26).

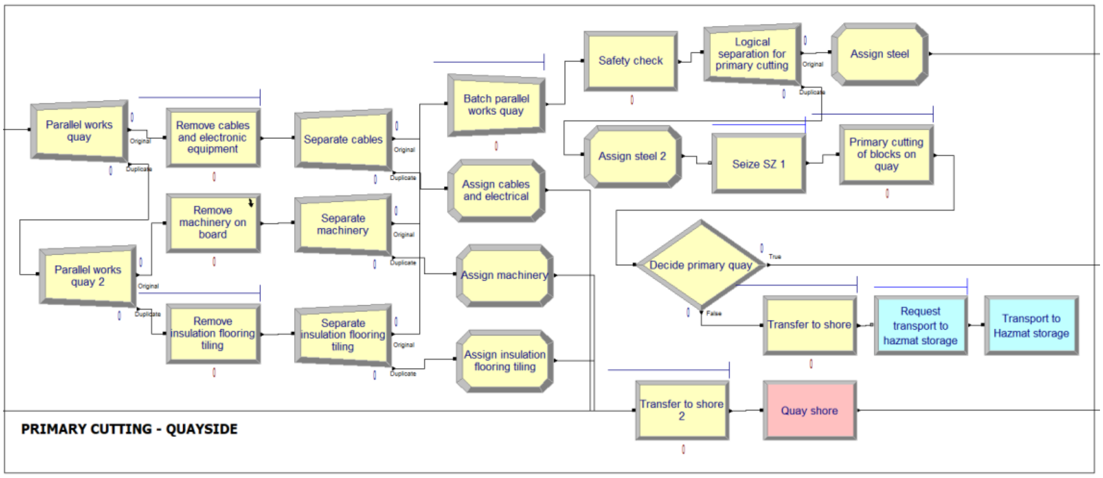


Figure 6.26: Primary cutting – Quayside in the model

Transfer to ramp

Once all the operation in the quay area is completed, the hull of the ship is transferred to the ramp using tugboats and the chainpuller (which is located on the ramp). This step uses a combination of delay and hold modules to ensure that the hull is not transferred to the ramp before the operation in the quayside is completed (Figure 6.27).

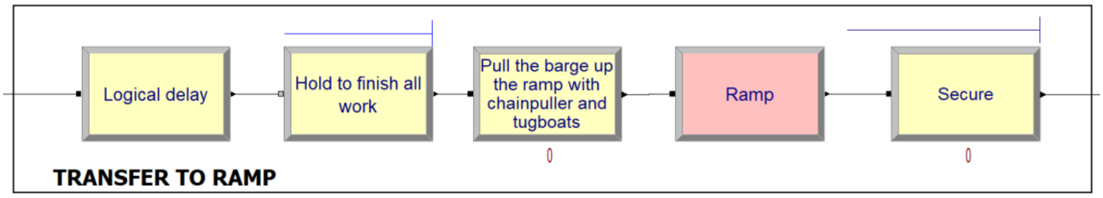


Figure 6.27: Transfer to ramp in the model

Then, hull is transferred to the ramp using the “Pull the barge up the ramp with chainpuller and tugboats” delay module. In order to change the station in the Arena module, Entity goes to the Ramp station manually and ship is then “Secured” by the workers”. After this step, cutting and dismantling on the ramp starts.

Cutting and dismantling on the ramp

This step first starts with the separation (duplication) of the blocks to model the block dismantling and cutting of the blocks. The blocks are handled using the process model “Cutting blocks” and Transferred to the secondary cutting zone.

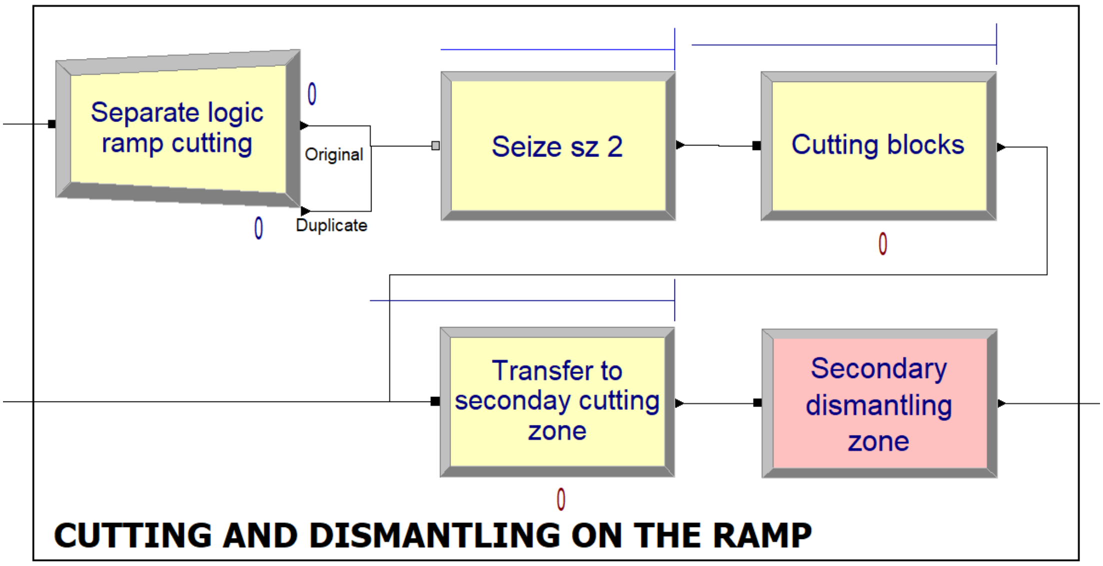


Figure 6.28: Cutting and dismantling on the ramp

Secondary cutting

After the blocks are transferred to the Secondary dismantling zone, these blocks are further cut according to the requirements of the steel mill. Then in order to represent the parts that are created after the cutting, blocks are further duplicated using the separation module. The duplication number in the Separate module are decided after the observations in the ship recycling yards. Subsequently, these panels and materials created in the process transported to segregation zone, workshop or hazardous material storage depending on the conditions of the decide module “Decide secondary zone”.

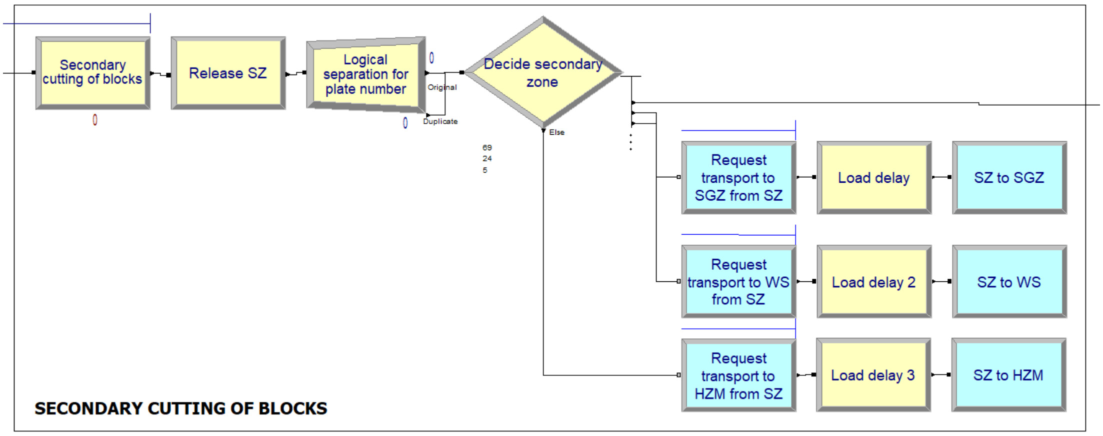


Figure 6.29: Secondary cutting of the blocks

Transport in the yard

This module handles the transportation of the material in the yard. Entities separated in the primary dismantling zone (quay) are handled through this module and entities are transferred to the relevant zone/storage (Figure 6.30).

The conditions in the Decide modules in the model are based on the material distribution assumption made in the previous section of this case study. Once the entity goes through the decide module according to the criteria, a available transporter is requested from the simulation system.

Setting the transport system up and establishing the links between stations is an important step in this part of the simulation. Once this is completed, distances between each station is defined. This was measured from the CAD drawings of the previously developed layouts Distances between the stations for each scenario created (Figure 6.22) are given in Table 6.8.

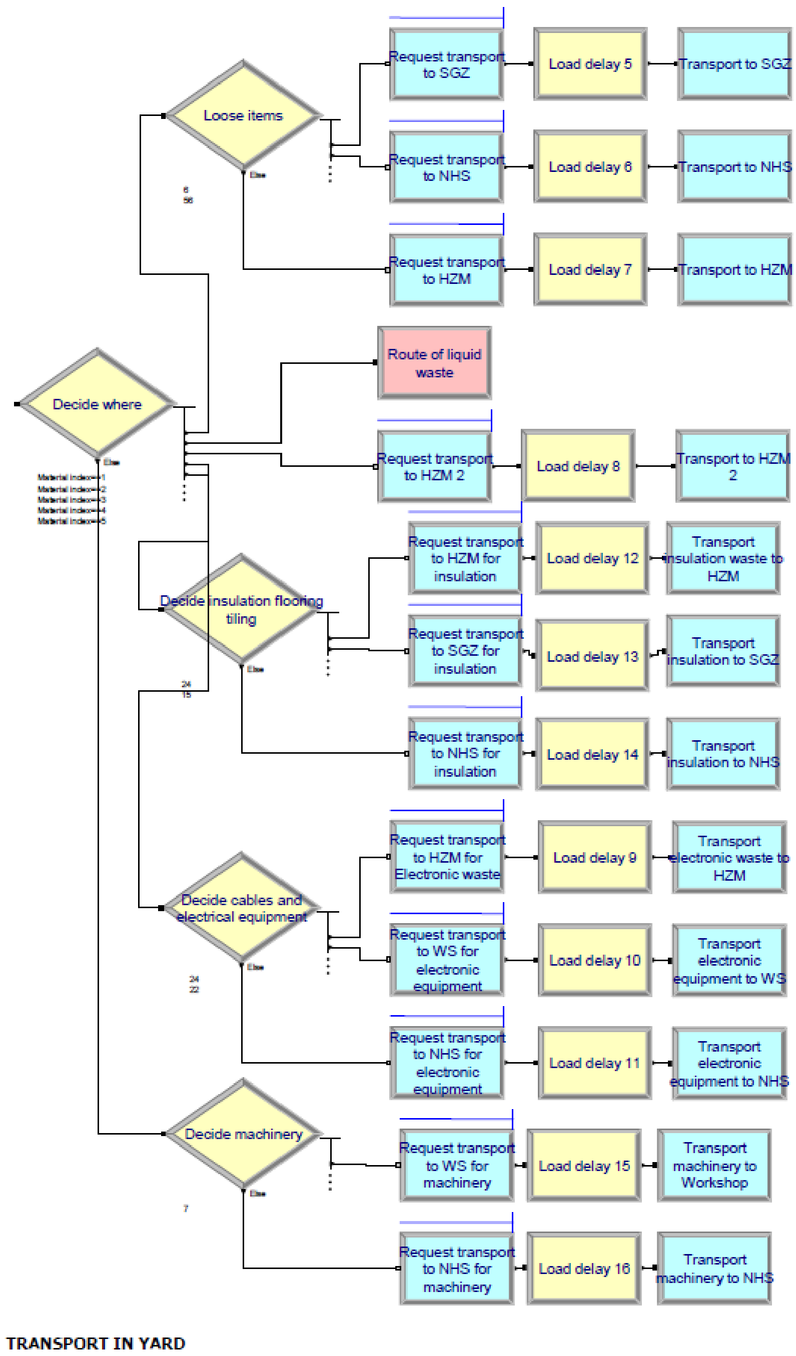


Figure 6.30: Transport in the yard

Table 6.8: Distance between stations (metres)

Alt. 1	Quay	Segregation	Hazmat store	Non hazmat	Workshop	Ramp	2nd dism. zone	Out	Load. Zone
Quay shore	X	50	95	57	42	68	31	90	93
Segregation	X	X	52	17	37	89	35	67	71

Hazmat store	X	X	X	49	64	81	81	60	53
Nonhazmat	X	X	X	X	24	117	98	90	95
Workshop	X	X	X	X	X	131	57	119	109
Ramp	X	X	X	X	X	X	28	90	47
Secondary dismantling zone	X	X	X	X	X	X	X	106	50
Out	X	X	X	X	X	X	X	X	18
Load. Zone	X	X	X	X	X	X	X	X	X

Alt 2	Quay	Segregation	Hazmat store	Non hazmat	Workshop	Ramp	2nd dism. zone	Out	Load. Zone
Quay shore	X	81	60	28	53	107	23	97	58
Segregation	X	X	120	78	100	26	27	22	65
Hazmat store	X	X	X	58	31	144	84	121	62
Nonhazmat	X	X	X	X	55	104	28	91	49
Workshop	X	X	X	X	X	118	58	98	45
Ramp	X	X	X	X	X	X	28	90	84
Secondary dismantling zone	X	X	X	X	X	X	X	64	40
Out	X	X	X	X	X	X	X	X	67
Load. Zone	X	X	X	X	X	X	X	X	X

Alt 3	Quay	Segregation	Hazmat store	Non hazmat	Workshop	Ramp	2nd dism. zone	Out	Load. Zone
Quay shore	X	30	76	46	76	115	31	95	90
Segregation	X	X	72	37	70	111	34	102	85
Hazmat store	X	X	X	42	64	105	75	86	68
Nonhazmat	X	X	X	X	51	40	29	69	72
Workshop	X	X	X	X	X	58	45	30	30
Ramp	X	X	X	X	X	X	28	90	35
Secondary dismantling zone	X	X	X	X	X	X	X	94	30
Out	X	X	X	X	X	X	X	X	25
Load. Zone	X	X	X	X	X	X	X	X	X

After the transport, entities reach their new station, materials in the transporter are unloaded through delay model, and the transporter is freed (Figure 6.31).

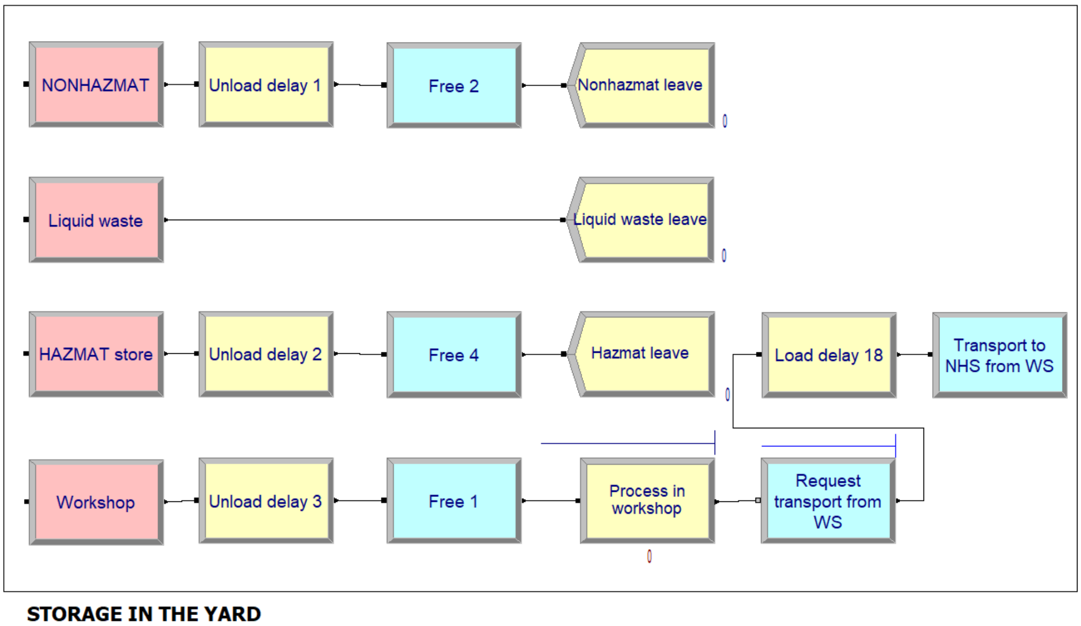


Figure 6.31: Storage in the yard

Another destination station of the materials from the ship is called segregation station. Materials other than steel is sent to storage and the steel obtained from the ship is transported out from the segregation zone.

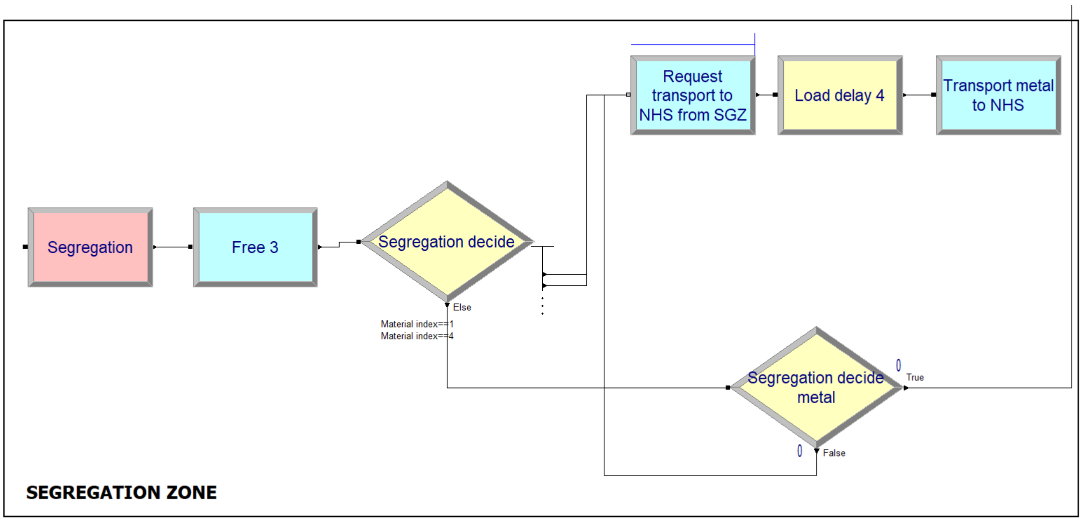


Figure 6.32: Operation in the segregation zone

Transfer from the yard

This operation will be conducted using Polygrab, operator and truck (and driver). Trucks will carry the steel parts to the steel mills close to the yard. This part of the model (Figure 6.33) starts with batch module to group the steel parts until enough material are collected to fill a truck. Adjustable batch is used for this step so that if the remaining material in the last batch are not enough to fill a truck, batch is automatically released to prevent the simulation running indefinitely. As a batch type, temporary batch is selected since the batch will be separated to model the '*loading the truck*' step accurately.

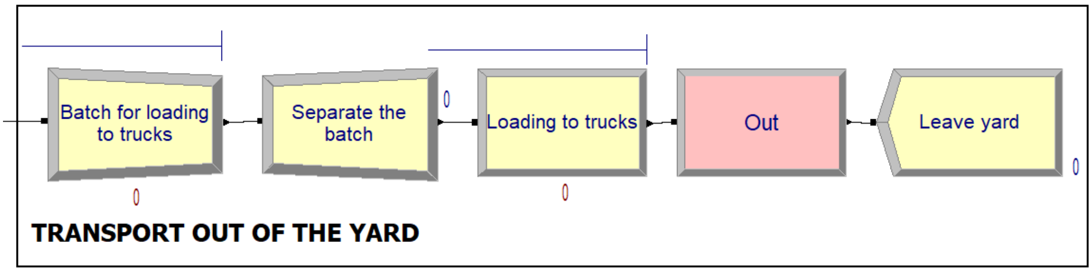


Figure 6.33: Loading operation and leaving the yard

Following the separation of the batch, loading the truck step is conducted by Polygrab, operator and a truck. For this step, operational data observed in the yard is used within the process module. After the loading, entities go through the "Out" station module and leaves the simulation.

Once the simulation is constructed, the working logic of the simulation should be tested and validated to check if the entities are moving correctly, logical modules (hold, seize, release, batch, request and so forth) are working correctly or transport modules have the required data. Several test runs were conducted in this model and modifications were made where necessary in order to eliminate the errors in the model building. The model which was reported above is the version that is freed of the errors, bugs or missing data as result of the validation.

6.2.2.2 Primary simulation results

In the previous section of this thesis, three different alternatives for the primary layout of the shipyard were developed. One of the main aims of layout planning is to minimise the material handling times in the facilities (Fu and Kaku, 1997), therefore, primary simulation will focus on minimising the overall material handling; block and material transfer times in the case of a ship recycling yard.

The Arena model introduced in the 6.2.2.1.4 was used in the primary simulation step for all the alternative layouts. The difference between the simulation for the alternative layouts is the travel distance (Table 6.8) of materials/equipment between each station.

For the primary simulation step, these three alternatives were run for 100 replications in order to find the best alternative out of the three layouts developed. Using the Simulation approach, many different criteria can be taken into account to compare and assess the different options. Since the simulation run for the draft layout is only a rough comparison, total operation time (in average) is a good starting point. The distribution of these replications are represented in the Figure 6.34.

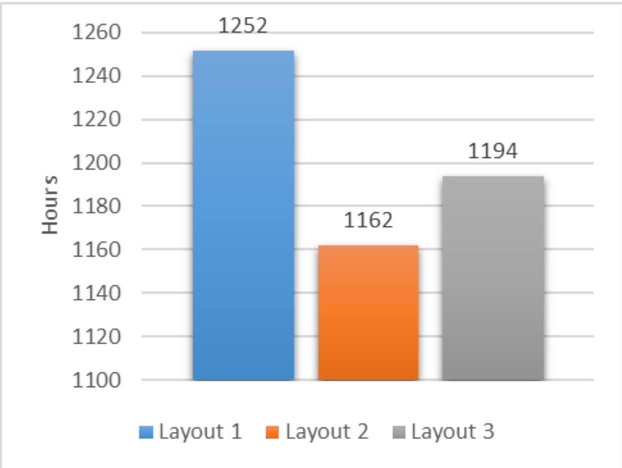


Figure 6.34: Total operation time for each layout (hours)

Following the 100 replications, total operation time (assuming 24 hours shifts) for the dismantling takes **1251 hours** (52 days) in average using the Layout 1 while the overall process is **1162 hours** (48 days) using the layout 2 and **1194**

hours (50 days) using the layout 3. The difference in the total operation time is caused due to the high transfer time between stations in layout 1 scenario. Other two scenarios, layouts 2 and 3, takes less time (around 10 and 6 days respectively) compared to layout 1 to complete the dismantling process.

Apart from the total operation time, overall cost is another factor that should be considered during the initial layout decision. In the cost calculation following has been considered

- Personnel costs
- External service costs (e.g. IHM, Tugboats)
- Equipment costs (e.g. oxy-fuel costs)
- Consumable costs (fuel gas, oxygen)
- Machinery operation and leasing costs (cranes, polygrabs)
- Transporter costs
- Yard's rent
- Ship's acquisition
- Port fees
- Insurance
- Finance cost
- Hazmat removal

In order to calculate the costs, following approach was used:

(resource cost + ship acquisition + yard rent+ port fees + insurance cost + finance cost+ hazmat removal) x contingency for unexpected expenditures.

On the other hand revenues were calculated through,

(Steel price per ton x steel output (tons)) + sales from other material + sale of machinery and equipment.

Personnel costs are included in the overall costs whether they are busy or idle, however, the oxy-fuel torch costs, consumable costs, machinery cost and transporter costs are included in the cost calculation according to the time they were busy. Their idle time cost (e.g. maintenance) are neglected. Costs of the external services are included in the total cost every time they are used. In order to keep the cost data confidential, the overall cost was converted to dimensionless quantity and the highest cost scenario, Layout 1, was accepted as 100% and the total cost in other scenarios were given as a fraction of this scenario.

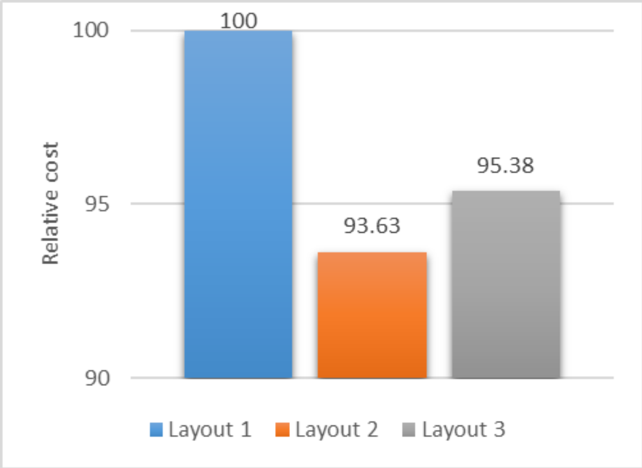


Figure 6.35: The total cost comparison of the alternative layouts

Even though there is not a major difference between the operation cost of the scenarios, layout 2 is the best option. Layout 2 costs almost 6.5% less than layout 1 and costs around 2% less compared to Layout 3. Combined with the reduced operation time, layout 2 can be considered as the best option to proceed with this case study. Reduced operation time hence the reduced cost will increase the output of the yard hence the profit of the yard will increase in the long term. In the basic layout design, the rough plan of the yard was created for all layouts. Next section will focus on improving the design of the layout 2

6.2.3 Detailed Design and Analysis Phase

6.2.3.1 Detailed layout design

In the previous section, simulation runs were conducted to compare and find the better layout out of the three alternatives generated. As a result of the primary simulation, Layout 2 (Alternative 2 in Figure 6.22) was found to be better solution compared to the other developed options. In this section, the developed layout will be improved through the modification of workspaces, areas, resources, and material flow.

Secondary cutting zone was identified as one of the most activity intense zones in the ship recycling yard in Chapter 4. Moreover, the primary simulation showed that the highest queue in the system occurs for the secondary zone for the secondary cutting. Therefore, it is important to work on the secondary cutting zone on the detailed design and simulation stage.

The current layout allows dismantling 25 blocks at the same time in the secondary dismantling zone. This constraint was not modelled in the primary simulation step but in order to model the ship recycling system accurately, it needs to be represented correctly. In order to model this constraint, area for blocks in the secondary dismantling zone were assumed as a resource and a "Seize" module before the primary cutting of the blocks were placed in the model. Before the block is cut in the primary cutting zone, system seizes a space for the block in the secondary cutting zone and proceeds to the primary cutting process, transfer to secondary dismantling zone and secondary dismantling process. After the secondary dismantling process is completed, space that the block was using freed through a "Release" module. However, if there is no available space, in other words, if there is no resource of "space" available, system also delays the primary cutting as there is no space to place the block after primary cutting.

In order to simplify the operation and keep the simulation focused on the secondary block cutting, simulation is kept limited to block cutting on the ramp, therefore all the activities related to primary cutting in the quay surveys, cleaning of the ship and removal of the equipment and machinery are removed from the simulation. The initial simulation of the 25 capacity secondary cutting zone completes the operation in 1135 hours in average. The average number of blocks in the queue for the "Seize module" is 149 blocks which means, block cutting operation in the ramp is paused 149 times due to the size constraint (and other constraints which will be focused later on) of the secondary cutting zone. This result demonstrates that the current production rate of the yard is limited with the capacity of the secondary cutting zone (and other resources); therefore, first attempt of the detailed layout design and simulation will be to improve the capacity of the secondary cutting zone.

The primary layout design step was concluded with the draft layout design in Figure 6.19. This step will modify this layout design in order to expand the secondary dismantling zone. The secondary dismantling zone modification will also require modification on the area, location and shapes of the other zones, therefore the capacity increase of the secondary dismantling zone is limited by the other (adjacent) stations. An initial study was conducted to store 35, blocks as a first step (Figure 6.36).

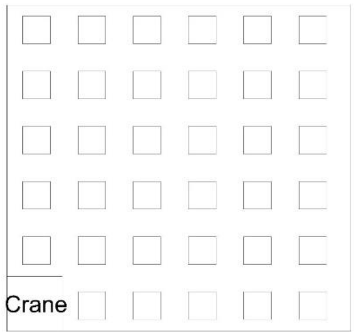


Figure 6.36: Simple representation of block distribution in secondary zone after modification.

In this scenario, operation is completed in average of 1134 hours after 100 replication. The average number of blocks in the queue for the “Seize module” is 139 blocks. Compared to the previous scenario of 25 block capacity, there is only a minor improvement on both the operation completion time and the block queue in the seize module. Also on the cost side, there is only a 0.3% decrease compared to smaller secondary cutting zone.

As an alternative approach, distance between the blocks in the secondary cutting zone was modified (in the initial assumptions of design, distance between the blocks was set to 5 meters). In order to develop an additional what-if scenario, this distance between blocks was reduced to 2.5 meters, which increased the block storage space in the secondary cutting zone to 77 blocks (Figure 6.37).

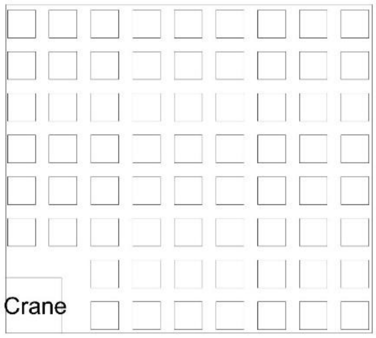


Figure 6.37: Alternate approach with the distance between blocks are reduced to 2.5 meters

This increase in the block storage space has decreased the average operation time by 6 hours to 1129 hours in total, which is a minor change, and decreased the overall queued blocks to 126 (Figure 6.38) and the cost by 0.04% (Figure 6.39).

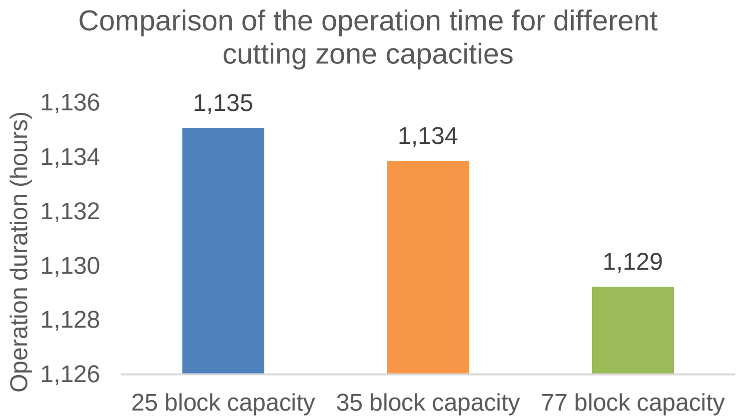


Figure 6.38: Operation time (in hours) for the different secondary cutting zone capacities

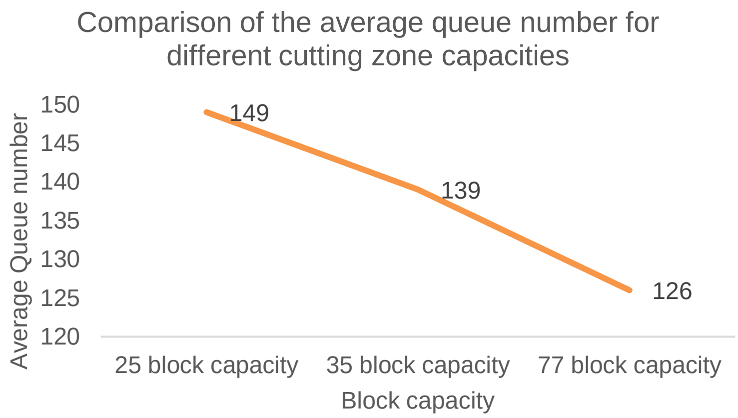
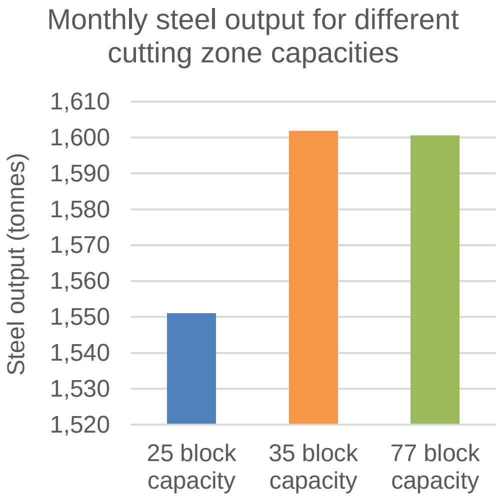


Figure 6.39: Average number of the block in queue

It is also useful to run the simulation for a specific repetition length instead of running the simulation with infinite length (in other words until the operation in secondary dismantling zone is completely finished). In order to compare the outputs of these three alternatives, simulation will be first run for a for a month to see the monthly output of steel.

Figure 6.40 represents the steel output in terms of tonnage and the estimated revenue of the steep output calculated through the steep output. In this scenario, 35-block capacity and 77-block capacity produces the similar amount of steel compared to 25-block capacity. Also, in terms of the revenue generated, 35-block capacity and 77-block capacity generates very close amount of revenue (and higher than 25-block capacity).



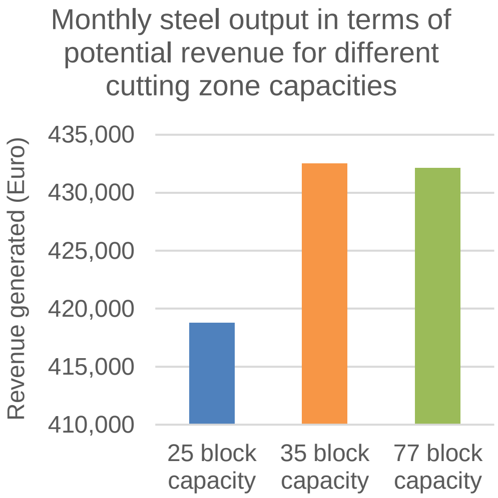


Figure 6.40: Steel output and revenue generated in a month (in Euro's, Price per ton steel is correct for August 2018)

Even though bigger improvement in the operation time, output and cost was expected after increasing the block storage capacity, the overall improvement in the process is seems minor for both capacity alternatives. This is due to the low number of resources, which also creates high number of delays and queues in the system. Therefore, this study will further investigate this operation through increasing the number of workers employed in the yard.

6.2.3.2 Detailed simulation for optimisation process

For this analysis, simulation model was modified to investigate the annual throughput of the secondary cutting zone. Five different cases for worker numbers were introduced in order to assess the performance of the different worker numbers with different cutting zone capacities.

Figure 6.41 represents the comparison in terms of the steel output of the yard in the given scenario, Figure 6.42 compares the potential revenue and Figure 6.43 shows the potential profit comparison.

In the six workers, twelve and twenty-four workers scenarios 35 block capacity in secondary zone is slightly more productive compared to 25 blocks and 77 blocks. However, after 48 workers and onwards all block capacities has the same output.

The base scenario, six workers, produces around 27,000 tons while 12 workers increases the production to 36,000-ton level. This increase in the production generates approximately 30% higher income in average (Figure 6.42) and around 25% higher profit with the given scenario (Figure 6.43). In addition 24-worker scenario increases the output to (in average) 43,000, and increases the income by 40% compared to base scenario, but the profit in this scenario is lower than 12-workers because of the increased worker costs while the revenue from steel stays similar. 48 worker produces the similar amount of steel and revenue due to the other constraints of the yard (crane, polygrab, schedules etc.) and this trend continues with the 96 workers. Also, 96-worker scenario end in a loss due to the high worker costs for this scenario.

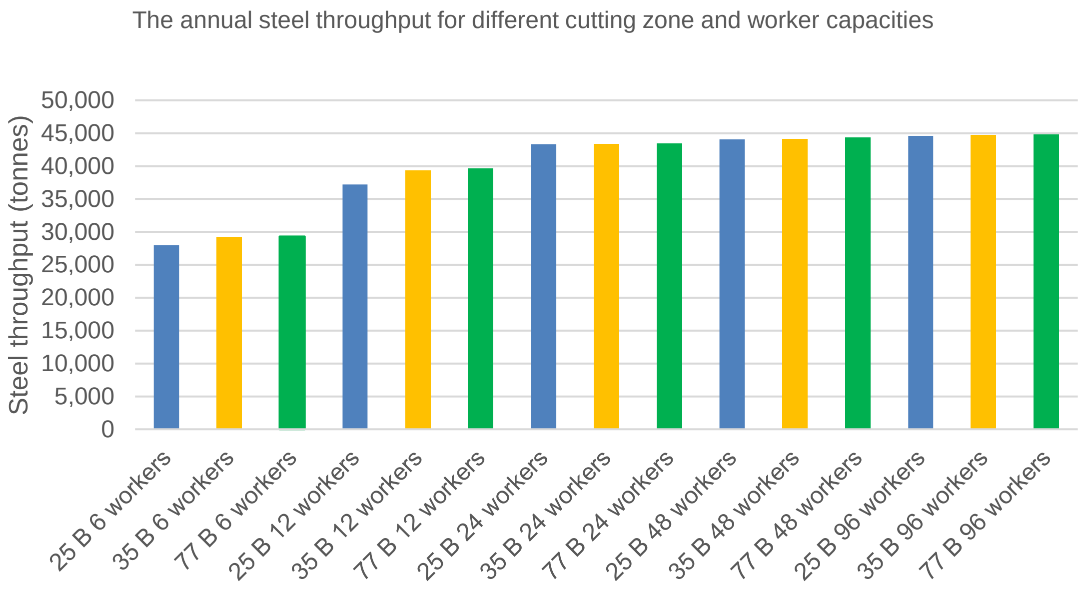


Figure 6.41: Comparison of the annual steel output (approximate) in terms of tonnage for different cutting zone and worker capacities

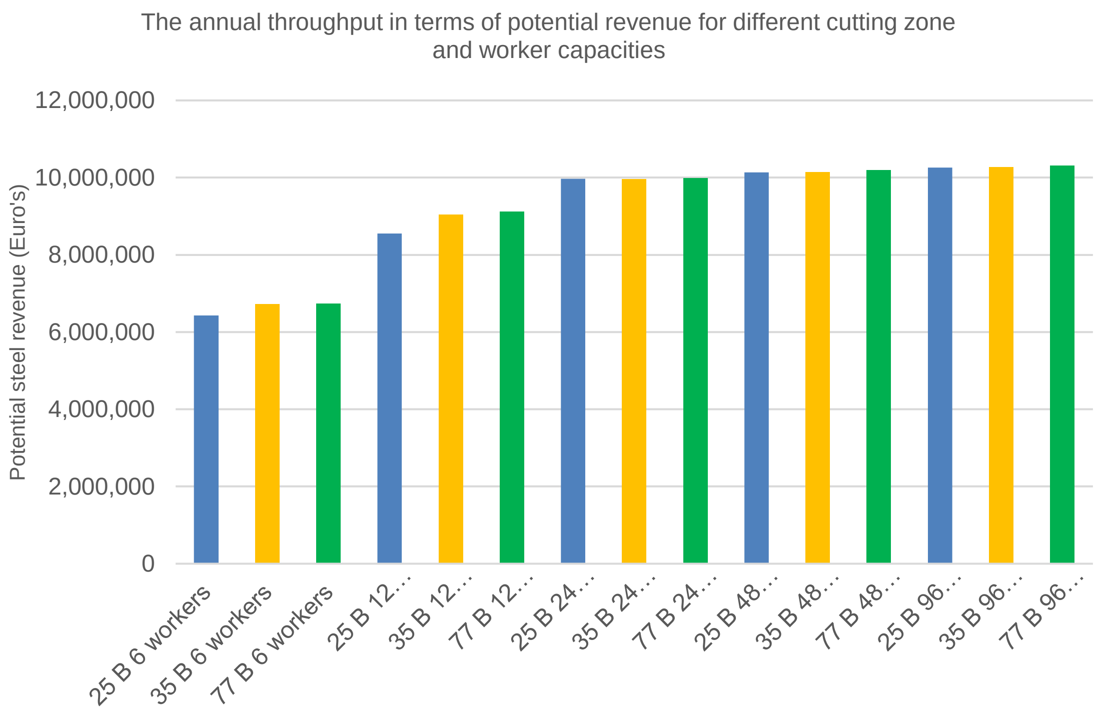


Figure 6.42: Comparison of the annual steel output (approximate) in terms of potential revenue for different cutting zone and worker capacities

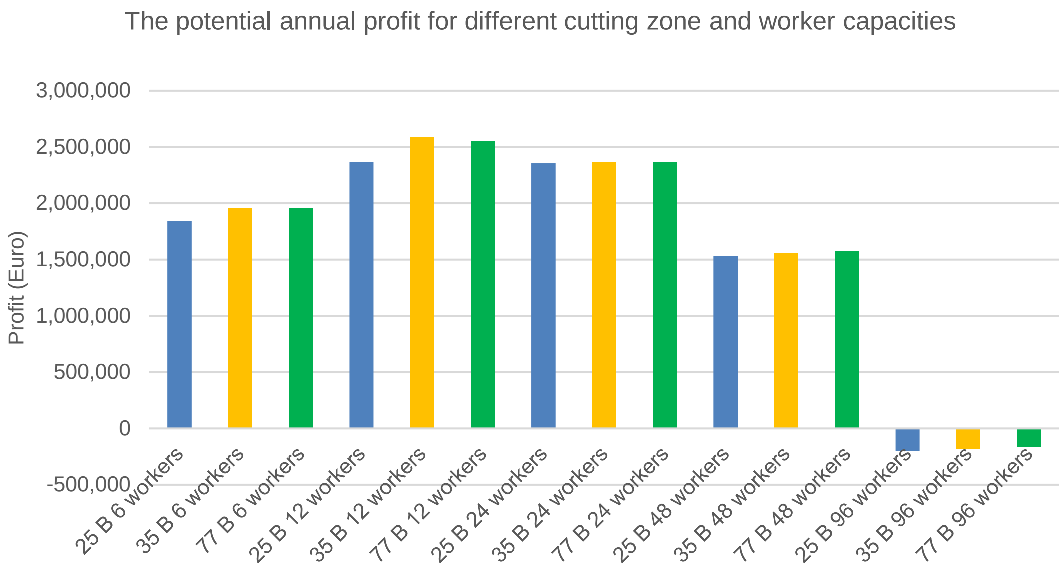


Figure 6.43: Comparison of the annual steel output (approximate) in terms of potential profit for different cutting zone and worker capacities

These analysis combined with the worker number gives more detailed information and insight about the design of the secondary cutting zone. The above analysis is repeated for 45, 55 and 65 block capacity scenarios for the secondary cutting zone however the performance of these scenarios are also very similar to 35 block capacity. Therefore, the secondary cutting zone will be modified to store maximum of 35 blocks at a time.

In order to create more space to increase the area of secondary cutting zone (and to accommodate 35-blocks), workshop and hazmat storage areas are modified, equipment storage is moved to the other side of waste treatment facility and loading zone is stretched to cover the storages, secondary dismantling zone and segregation zone for non-hazmat (Figure 6.44).

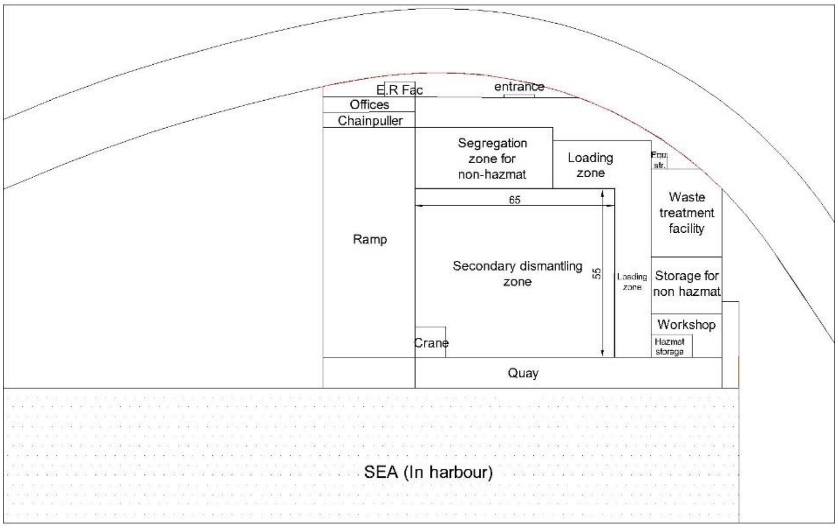


Figure 6.44: Modified layout to increase the secondary dismantling zone area

This optimization study conducted on the secondary dismantling zone can also be applied to other zones such as the workshop, storages (hazmat and non-hazmat), loading zone or even with ramp and quay (to host several ships at the same time) using the simulation approach introduced in this chapter.

6.2.3.2.1 Zone-Facility Integrated Simulation

This phase of the case study will integrate the secondary cutting zone simulation to the facility wide simulation to further improve the yard's operation. Therefore, the first step is to add the details in to the simulation that were neglected in the primary simulation step, such as torches as resources, cost of torches, zone constraints (e.g. "Secondary cutting zone" resource which was introduced in the previous step), working schedules in detail. Next, an overall validation of the simulation should be done to check the logic and once the final model is validated, further analysis can be conducted.

In order to represent the space occupied by the block in secondary cutting zone, two seize modules are placed for primary cutting steps: one is before the "Primary cutting of blocks on quay" and the other is before the "Cutting Blocks" to secure a space in the secondary cutting zone before cutting the block in primary cutting zone. In order to free the space after the secondary dismantling, a release module that frees the secondary cutting zone space is added to the module Figure 6.45.

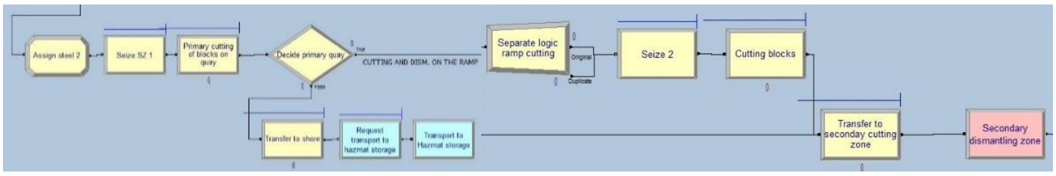


Figure 6.45: Placement of Seize modules

Resource - Basic Process

	Name	Type	Capacity	Schedule Name	Schedule Rule
1	Technical manager	Based on Schedule	Manager schedule	Manager schedule	Preempt
2	Tugboats	Fixed Capacity	2	2	Wait
3	Foreman	Based on Schedule	Foreman schedule	Foreman schedule	Preempt
4	Workers	Based on Schedule	Worker schedule	Worker schedule	Preempt
5	Crane	Fixed Capacity	1	1	Wait
6	Operator	Based on Schedule	Operator schedule	Operator schedule	Preempt
7	Polygrab	Fixed Capacity	1	1	Wait
8	Torch	Fixed Capacity	30	30	Wait
9	Secondary cutting zone slot	Fixed Capacity	35	35	Wait

Figure 6.46: Resources in the system

Furthermore, resources in the system were introduced with more details. Detailed worker, (polygrab and crane) operator, and foreman schedules, were introduced in the model along with the detailed costs. Four different schedules were introduced in the system; Worker schedule, Foreman schedule, Manager schedule and Operator schedule (Figure 6.47). Schedules are based on the daily working hours between 9.00-12.00 and 13.00-17.30. Out of these hours, capacities of the manager, operator, foreman and worker are set to 0. Foreman and manager capacities are set to “1” in the working hours. Since the workers and the operators conduct the majority of the manual work in the yard, their availability or changes in number significantly impacts the operation. Therefore, an easy-to-modify option is needed to modify the number of workers during the analysis. In order to manage the modification, the number of workers and operators are defined as variables. Tools and machinery are assumed to be fixed, therefore always in the yard, and they are not tied to any schedules.

Schedule - Basic Process

	Name	Type	Time Units	Scale Factor	File Name	Durations
1 ▶	Worker schedule	Capacity	Halfhours	1.0		5 rows
2	Foreman schedule	Capacity	Halfhours	1.0		5 rows
3	Manager schedule	Capacity	Halfhours	1.0		5 rows
4	Operator schedule	Capacity	Halfhours	1.0		5 rows
	Double-click here to add a new row.					

Figure 6.47: Introduced schedules in the model

During the detailed simulation step, more than 250 scenarios were run (100 times per scenario as the sensitivity is not the primary objective) to find the best resource combination in order to meet the initial requirements of the yard's owner on the capacity expectation (6.2.1.1);

"*The initial estimation of the investors for the yard is that the yard is expected recycle 30000 t scrap volume yearly, but the owner would like to achieve 60000t scrap volume (In other words, 12 medium size vessels of 5.000 t).* "

The next section will summarize the outputs of these scenarios and will identify the best option in terms of resource management in the yard.

6.2.3.2.2 Simulation Runs, Results and Analysis

Base scenario was to run 200 replications first to find out whether the yard owners' initial plan of resources will be sufficient to reach the capacity expectation. The initial intention of the yard owner was to employ one foreman, one (crane and polygrab) operator, six workers and to buy one crane and one polygrab to conduct the operation in the yard.

Using the initial number of the workers, the completion of the dismantling operation for an 11,000LDT ship takes 2,997 hours in average (Figure 6.48). When the total hours are converted to working days, the operation around 125 working days.

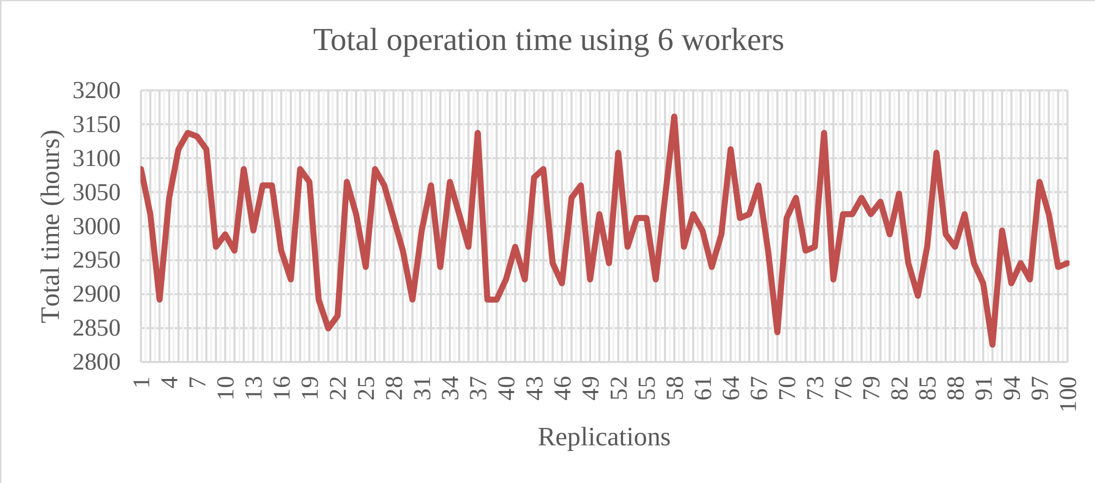


Figure 6.48: Total operation time when using 6 workers (hours)

Using Jain's method for material flow from end of life ships, 9,000 tonnes of metals was previously calculated to obtain around at the end of this operation. Assuming all this metal is sellable to the mill, the revenue of the yard is calculated through the price per tonnes times the tonnes of metals acquired from the ship. Moreover, an interview is conducted with an expert, who sells used machinery and equipment from end-of-life ships, to accurately calculate the revenue generated from the machinery and equipment from the ship. Similar to previous analysis the personnel costs, equipment costs, ship purchase cost, rent for the yard's area, insurance costs, leasing costs of machinery (crane, polygrab) are included. Using this calculation method (Table 6.9), yard generates 40.71 Euro's profit per LDT.

Table 6.9: Details of cost calculation

Item	Value
Resource cost (R)	196,854
Acquisition cost (A)	1,540,000
Rent for the land (L)	45,000
Machinery cost (M)	48,000
Port fees (P)	61,000
Insurance (I)	4,250
Finance cost (F)	57,750
Total cost (T)= (R+A+L+M+P+F)	1,952,854
Real Cost (T*1.03)	2,011,440
Steel Revenue (S) =	2,459,325
Other metals revenue (O)	104,225
Machinery Revenue (MR)	370,800

Total Income = S+O+MR	2,934,350
Total profit (TP) = RC- TI	447,885
Profit per ton steel (TP/LDT)	40.71

In order to check for the annual output, the limit on incoming ships are removed and the simulation was changed to introduce additional ship once the simulation is completed. Moreover, the assumption in this scenario that several identical 11,000 LDT ships to be purchased by the yard. This scenario was run for a year and the steel output from the yard shows us that the yard with its current capacity can finish the second ship, and starts the third ship before the simulation ends. Dismantling two ships and starting the third one brings the total output of the yard annually around 25,000 LDT, which is well below the owner's requirement from the yard. The system should be investigated in order to identify the bottleneck areas that are causing the underperformance and address these problems.

The main queue in the production happens on the primary cutting in the ramp and the secondary dismantling zones. The accumulated wait time of the all blocks in the cutting in is step 11,429 hours, and 8,996 hours in the secondary cutting zone. The queue in the primary cutting zone is also caused due to the queue in the secondary cutting zone as the area and the number of workers limits the production in this zone. Other cause of the low performance can be the crane's performance, however, when checked the maximum queue occurs in this section is only 30 parts. Moreover, while the utilisation of the crane for one crane scenario is 0.105 in average, utilisation of the crane is 0.57 for two cranes. Therefore, in this case crane does not cause a bottleneck in the system.

One of the options to overcome the productivity problem in the primary and secondary dismantling zone is to increase the number of workers. Therefore, simulation was repeated for 12, 18, 24, 30, 36, 42 and 48 worker combinations. Similar to above, total operation time to dismantle one ship and the annual output of the yard will be considered. Therefore two different simulations for each alternative will be conducted.

Using 12 workers instead of six workers reduces the average time to fully complete the dismantling operation by 20% and brings it down to 2,400 hours (Figure 6.49) while decreasing the total profit by 1% and increasing the overall cost 0.1% hence decreasing the profit per ton to 40.48 Euro’s.

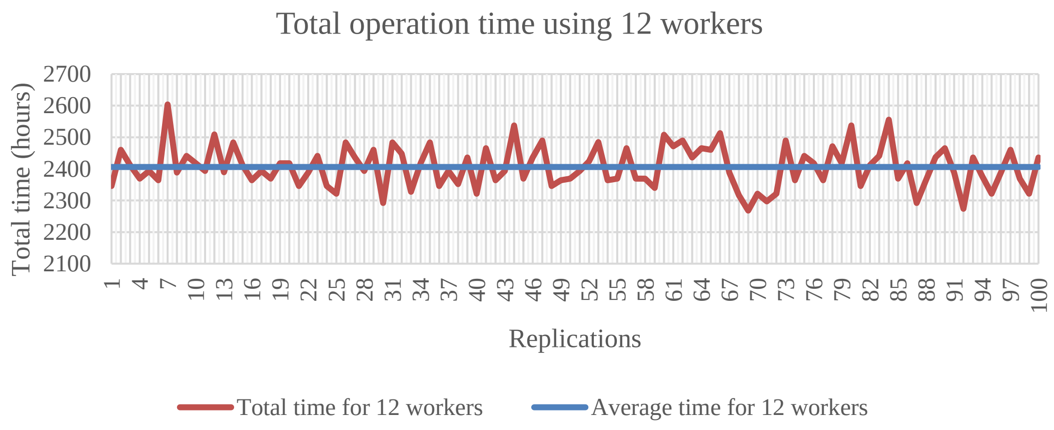


Figure 6.49: Total operation time using 12 workers

Figure 6.50 compares the total dismantling duration for all worker combinations. 18 worker completes the operation in 2,200 hours, 24 workers completes 2,116 hours but after this the decrease in the operation time becomes minor as the other (storage, zone, transport) limits of the yard becomes effective on the output. Moreover, even though the 48 workers has the least duration, profit should be considered before making a decision (Figure 6.51).

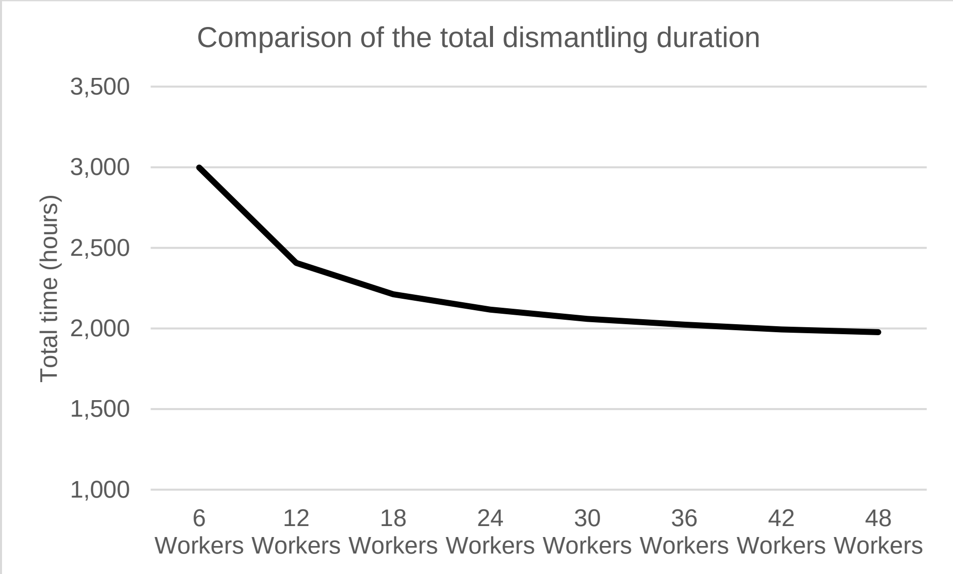


Figure 6.50: Comparison of the total dismantling duration

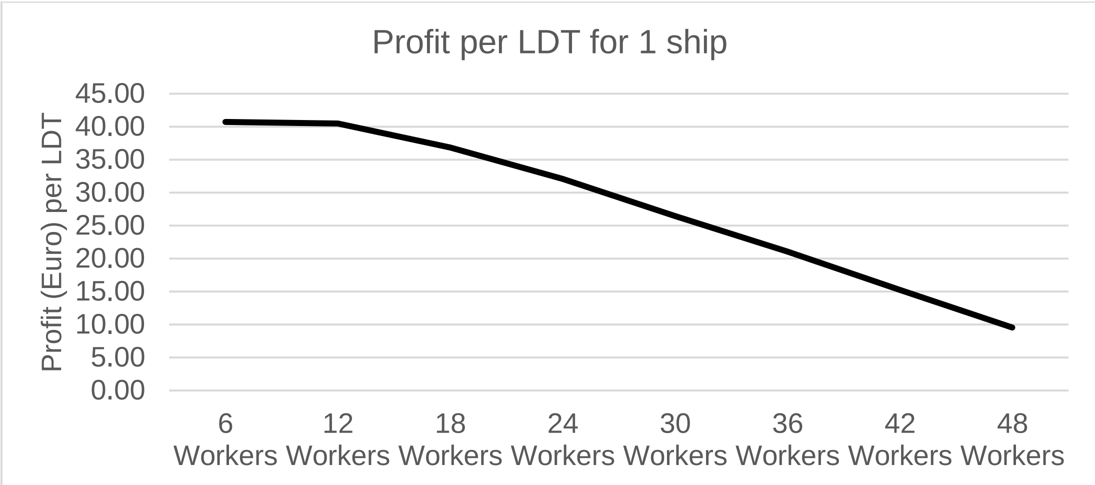


Figure 6.51: Profit per LDT for one ship

Even though the 48 workers finishes the dismantling of a ship quickest, the cost is the highest compared to all worker alternatives. Moreover, due to the yard's limits on other resources and physical capacities, production rate reaches to maximum around 32,000 LDT (Figure 6.52), which means the revenue of the yard also reaches its maximum under the given circumstances. Combined with the high cost, 48 workers produces the least profit annually compared to the other worker scenarios (Figure 6.51). This scenario shows us that instead of 6 workers, yard can employ 12 or more workers and meet the current goal of dismantling 30,000 LDT's per year. This is made under the assumption that yard buys ships around 10,000 LDT (or equivalent of multiples, e.g. 2 ships of 5,000 LDT's).

Figure 6.52: LDT dismantled annually

In addition to the worker numbers, operator, polygrab and crane numbers were also modified to assess the impact of these on the production. However, the total LDT dismantled annually only changed over 1% even though costs increased more than 10% when two operators and two polygrabs are employed, and more than 20% when an additional crane added. Considering the investment cost as well, this scenario will not be investigated further until a solution is found. When a suitable solution is found, these scenarios should be reconsidered with combination of the solution.

As the year-long simulation shows that system meets the goal with 3 ships yearly (after the above modification), it is time to understand whether the yard can meet the future goal for 60,000LDT's. In order to test this scenario, six ships of 11,000 LDT ships are introduced to the system through the *create module* with constant arrival time of 30 days. Even though it was shown that yard can meet the current goal of 30,000 LDT with increased resources, the performance of the system is not satisfactory to meet the 60,000 LDT goal. The average dismantling duration for different worker numbers are given in Figure 6.53. Six workers completes the dismantling operation for all the vessels around 15,500 hours, and the number goes down to around 8,400 hours with 48 workers. Figure 6.53 shows that the complete dismantling of the six ships takes minimum of 8,400 hours, which is equal to 353.5 work-days (around one and half year). Even though six ships takes the longest time, it is the most profitable choice (along with 12 workers) for the yard (Figure 6.54).

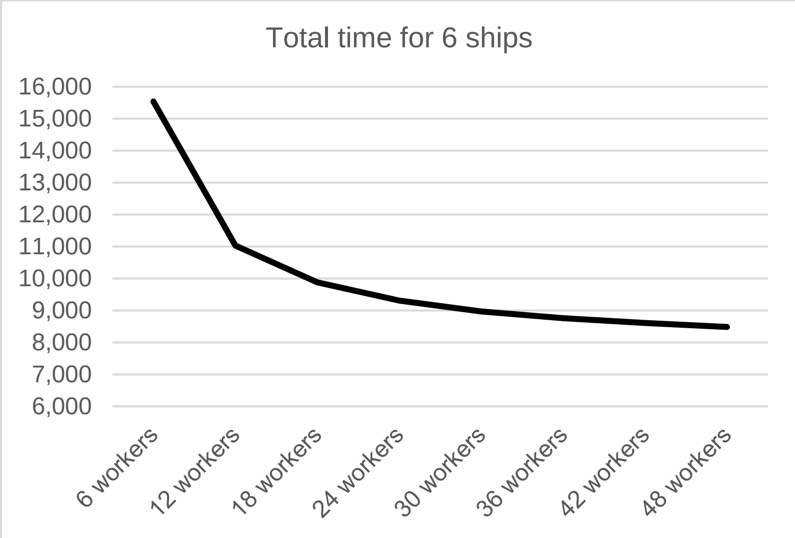


Figure 6.53: Total time to dismantle six ship according to different worker numbers

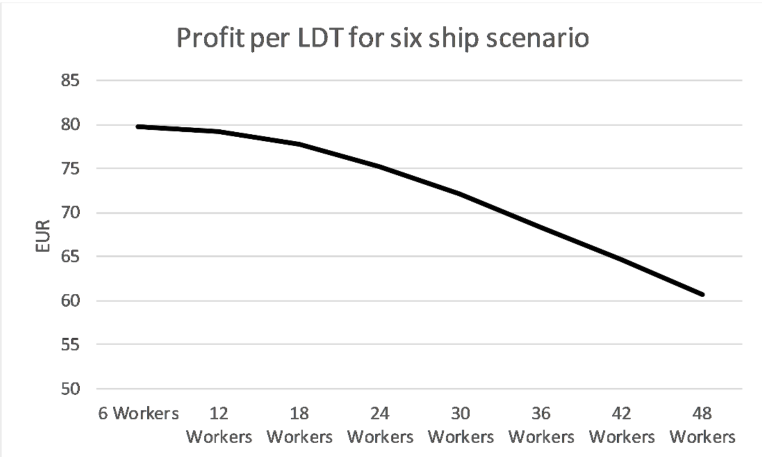


Figure 6.54: Profit per LDT

In the annual (251 days) run, workers manage to dismantle up to 44,700 tons of steel out of 55,000 possible. The minimum output in the year belongs to six-worker scenario, while the rest of the worker scenarios' output is very close. On the other hand similar to previous scenarios in this section- six worker scenario has the minimum cost even though six worker scenario creates the lowest output in terms of steel. Cost of the 48 workers is more than 4 times higher than the cost of six workers, combined with the other expenses of the process, employing 48 workers has 13% more cost respectively to six workers (Figure 6.55).

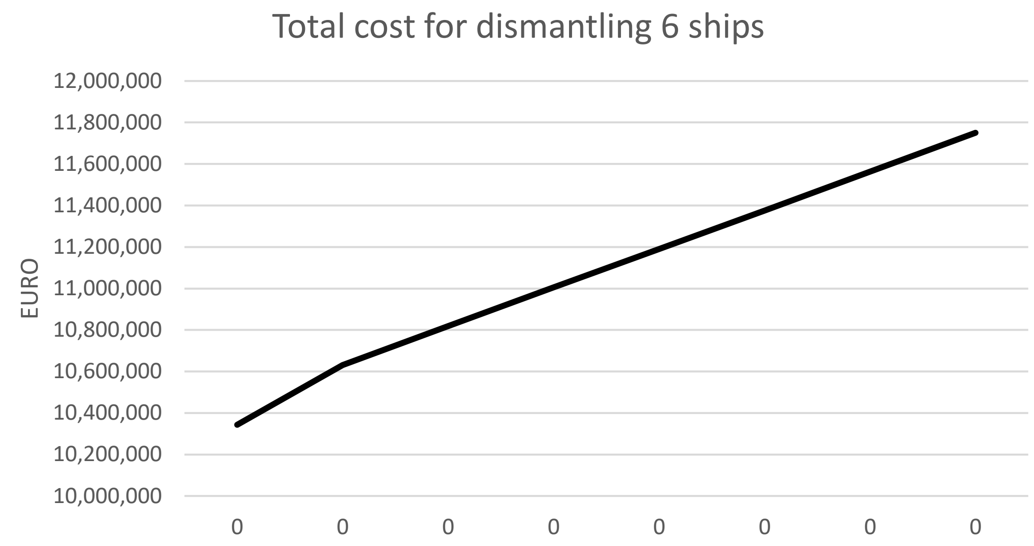


Figure 6.55: Total cost of the operation in a year

The increase in the cost also reflected to profit of the yard which reduces the profit per ton steel by €20 (Figure 6.56). Looking from the profit in a year perspective, combined with low cost and higher output, 12 worker scenario creates the highest profit, followed by 18 worker and 24 worker scenarios with very small difference (Figure 6.57).

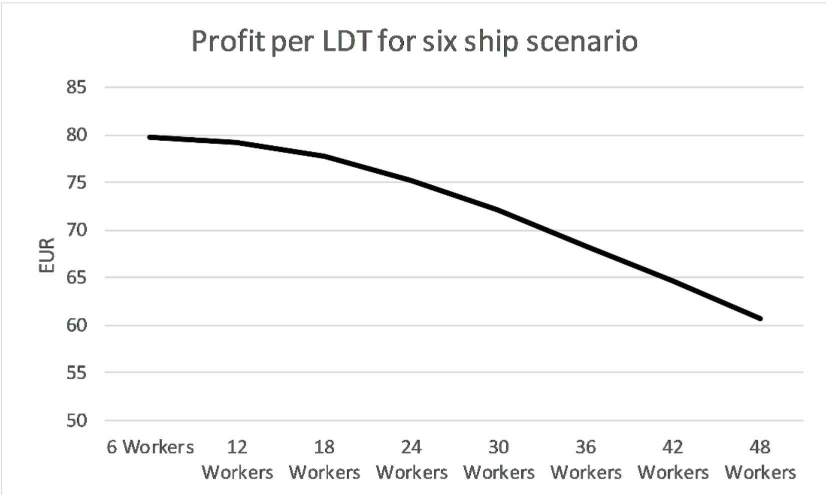


Figure 6.56: Profit per ton steel obtained from year long simulations

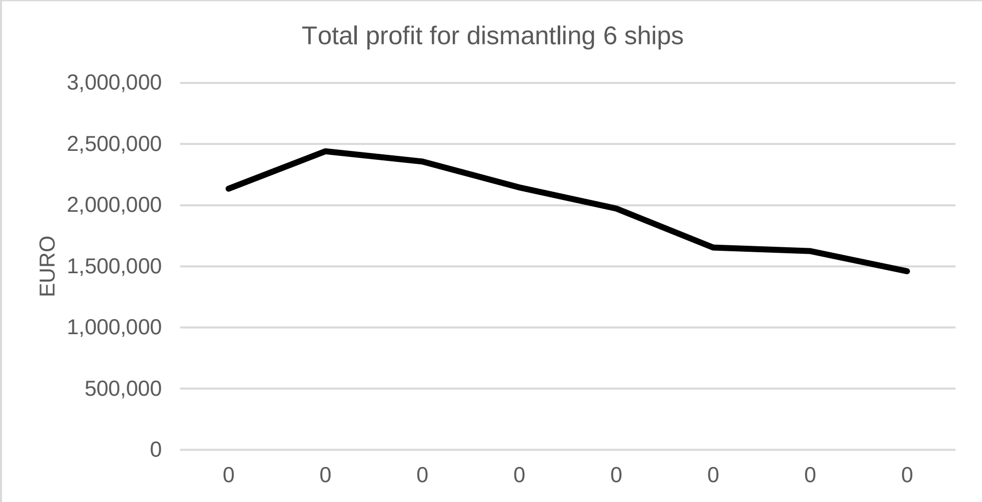


Figure 6.57: Total profit in a year

As mentioned above, two different runs were conducted for the six-ship scenario, year-long scenario and the scenario without time limit to find out the actual time required to dismantle the six ships in this yard. Total time required were summarized in Figure 6.53 which showed that the time required ranges from 15,000 hours to 8,400 hours. On the cost side of these scenarios; as expected six workers has the minimum cost and the 48 worker has the highest cost (cost of 48 hours is 2.4 times higher than the cost of six worker operation). Also, as expected, the cost of the complete dismantling operation is around 30% higher than the annual run. The segregation and transfer of other materials affects the operation significantly and increases the cost. The increased cost of the operation also effects the profit, profit per ton is decreased for all worker alternatives by couple of Euro’s (Figure 6.56Figure 6.57).

The results of the current state of the yard shows that short term goal (30,000LDT per year) is achieved now. Long term goal (60,000) is not achievable with the current constraints and limits of the yard. In this PhD study, alternative resources were combined to overcome these bottlenecks and reach the desired capacity, however, this aim was not satisfied on none of the analysis. One of the solutions to achieve the goal can be to increase the area of the yard which will increase the area of dismantling zones and will help accommodating several ships at the same time. Other solution is the implementation of more modern technologies to ship recycling operations in the yard. A suitable place to start to implement modern technologies is the cutting operation, because it is an intense activity throughout the operation and the oxy-fuel cutting is quite an outdated technology. Therefore, further optimisation of the ship recycling yard will continue with implementation of an alternative cutting method. Details of the selection of alternative cutting method, simulation method and the results will be given in Chapter 7 of this thesis.

6.3 Chapter Summary

This chapter has summarized the overall layout development and yard optimisation framework using the simulation. Also, an alternative approach to cutting operation was presented to demonstrate the different uses of discrete event simulation in ship recycling yards. The findings of this chapter can guide the researchers as well as ship recycling stakeholders on the design of new facilities, improvement of existing facilities and improvement of the operations.

Chapter 7 Case Study on Specific Process Improvement and Optimisation

Use of Discrete Event Simulation for the Comparison of Different Metal Cutting Methods in Ship Recycling Industry

7.1 Chapter Overview

The main aim of this chapter is to increase the productivity of the ship recycling yard through the implementation of different cutting methods which are applied to the ship recycling industry. This chapter first identifies the cutting technologies suitable for the ship recycling industry and then compares the performance of these technologies using the discrete event simulation approach. Following these analyses this Chapter combines the technology approach with the Case study yard introduced in the Chapter 6.

7.2 Identification of the problem

One of the most performed activities in both primary and secondary dismantling zones in ship recycling yards is the cutting of the steel. During this process oxy-fuel torches are being used by the workers due to the very low investment cost, low training need and ease of operation. However, especially in the secondary cutting zone, performances of the cutters are very low. This is due to the low production rate of oxy-fuel cutting torches. Therefore, there is a need for a study to investigate the alternative cutting methods and compare with the currently used oxy-fuel cutting method.

In the observed ship recycling yards, the secondary cutting zone was identified as the bottleneck of the system when the blocks in the secondary cutting cannot be handled fast enough and the block storage area becomes insufficient for additional blocks. This causes a delay on the clearance of the primary zone for the new ships which in long-term decreases the capacity of the ship recycling yard.

7.3 Approach Adopted for this Case Study

Three different cutting methods; plasma cutting, oxy-fuel cutting, and water-jet cutting were modelled and simulated to compare these cutting scenarios to find cost-effective and high-performance alternatives to the oxy-fuel cutting. The approach followed in this chapter (Figure 7.1) consists of six steps. The first step was to review the existing studies on cutting methods, in order to find the best approach for the identified problem. Next, the cutting methods were investigated and comparison was made to select the most suitable alternative to oxy-fuel cutting. The next step of the study was to select the blocks from a ship to model the cutting operation and modelling the dismantling operation in the simulation environment. In the final step, the analysis of the current and the alternative scenarios for the system were run in the ARENA software and performances of these scenarios were compared to find the optimum cutting method for ship recycling.

Figure 7.1: Simulation methodology followed in this study.

7.4 Review of the Studies Focused on Cutting Optimisation

Specifically in ship recycling industry, there are not many studies that investigate the performance of different technologies for cutting the steel. The most comprehensive study, DIVEST (2008-2011), developed a value model as part of the EU funded FP6 project. One of the aims of the developed value model was to compare different ship recycling options. In the report, one of the case studies was to compare oxy-acetylene cutting to the oxy-propane torch (DIVEST, 2011). However, this study only approaches the problem on the economic perspective, and there is no in-depth productivity analysis as part of this study. DIVEST also assessed the feasibility of different cutting and surface cleaning technologies (DIVEST, 2009c). In this study, key performance indicators (such as technology readiness level, Investment, installation cost, and so forth) were defined and assessed each technology with these key performance indicators whether these methods were usable in ship recycling or not. Moreover, authors of the report have collected information about cutting rates, costs, technology readiness levels, benefits and disadvantages (DIVEST, 2009a). However, this study was only on a theoretical level and only used estimations on the performance and operation costs. Even though this study provides a good starting point, it does not include in-depth information on the practical implementation of these cutting rates.

McKenna and Das (2008) proposed different cutting and removal methods such as caustic stripping, ice jetting, water jet blasting and cutting, sponge jet blasting and mobile shears improve the ship recycling regarding safety, economy and environment-friendly. However, the study is limited to health and safety improvement, and it is only suggestions for alternatives.

Deshpande et al. (2010) conducted a time-motion study to estimate the inputs (labour, oxygen and fuel) and outputs (emissions to air as well as deposition of paint and steel on intertidal sediment) during the cutting operation using oxy-fuel torches. The analysis of inputs showed that 6.2 kg of fuel is consumed per km of plate cut per mm plate thickness. On the output side, CO_2 emissions were estimated as 21.77 kg per km of plate cut length per mm of plate thickness (Deshpande et al., 2010). Findings of this study can be utilised to estimate the CO_2 emmissions and to find the CO_2 reductions after the optimisation process.

In 2010, a pilot project was conducted in a ship recycling yard to test different ship recycling techniques including waterjet cutting (Urano, 2012b, Shimizu et al., 2012a). In this study, 45,706 GT Pure Car Carrier was selected as a case study and all the steps of the recycling operations were reported (Urano, 2012b). As part of this pilot project, waterjet cutting was also considered for application on ship recycling. A special waterjet cutting machine was developed, which is lighter and stronger than usual waterjet cutting machines (Urano, 2012b). This study demonstrated the possible use of waterjet cutters in ship recycling, especially in the areas with high explosion and fire risks.

The summary of these studies are shown in Table 7.1.

Table 7.1: Summary of the studies on technology comparison for ship recycling

Author/ Project	Year	Pro's	Con's
McKenna, and Das	2008	Investigation of different technologies for ship recycling	Limited to HSE improvement and limited as a suggestion
DIVEST	2009	Investigation of key performance indicators (TRL, investment, installation cost, etc.)	Theoretical level, no in depth information on practical implementation.
Deshpande et al.	2010	Useful time motion study to estimate inputs and outputs during cutting.	
Urano et al.	2012	Investigation of waterjet cutting machine	Good practical implementation in an actual case but does not provide guidance for future studies.

The review of the studies also shows that there is a need for a comprehensive study to compare the cutting methods for the ship recycling industry. At this point, DIVEST project's technology list will be utilised and this research will build on that. For example production rates will be checked and updated as DIVEST finished seven years ago. New technologies will also be included in this list. As a starting point, the following methods were investigated;

1. Oxy-acetylene
2. Abrasive Waterjet
3. Mobile shear
4. Handheld shears
5. Abrasive cutting wheel
6. Grinder
7. Saws
8. Laser

This study will only focus on the hot cutting methods, as the hot cutting is the dominant cutting approach in the yards. Therefore, only the oxy-acetylene, abrasive water jet and laser from the above list can be investigated further. On the other hand, laser cutting is relatively a new technology, and the initial cost of laser cutting equipment is exceptionally high (£50,000+). Also, the operation of the laser cutting equipment requires specific measures for health and safety and the mobility of the laser cutting system is minimal. Considering the nature of the ship recycling, laser cutting system will not be assessed as part of this study.

In addition to these methods identified by DIVEST Project, other cutting methods were also investigated in similar industries and plasma cutting technology is identified as a viable alternative to oxy-fuel cutting as plasma cutting technology is high-speed and reliable technology. Plasma cutting is not a new technology, but the operation and the investment of the system was expensive. The advancement in the technology lowered both investment and operation costs of plasma cutting.

To sum up, three technologies are decided to be analysed further in this part of this study. As the current technology, oxy-fuel cutting will be included in this study. In order to set the baseline and compare to other methods, oxy-fuel will be investigated. Secondly, plasma cutting technology will be investigated as it is a modern and strong alternative to oxy-fuel cutting. Lastly, abrasive waterjet cutting will be investigated to demonstrate the different cutting approaches and their feasibility in ship recycling industry.

After the identification of technologies, the next step is a review of the literature for the comparison studies on these cutting methods. It was found out that there is no comprehensive study for the comparison of the productivity of these methods in ship recycling. Apart from the ship recycling industry, similar industries were also investigated to find the studies in the literature. There are several comparison studies for the selected technologies, but these studies have their limitations; for example, comparison of plasma, waterjet cutting, and the laser was made by Krajcarz (2014). However, this study was done for production cutting and it was limited to the general review of these methods. Moreover, there are several examples of comparison of the generic properties of these cutting methods. To name a few; OMAX (2017a) compares the generic properties of Waterjet and Plasma cutting methods while Juliet (2015) compares the general properties laser cutting with traditional cutting methods (waterjet, plasma, Oxy-fuel and mechanical cutting). These studies do not go beyond explaining the available technologies, their benefits and shortcomings. Therefore, it is not certain whether the findings of these studies can be transferred to ship recycling. Hence, it is important to investigate these cutting technologies in specific ship recycling technologies (Advantages and disadvantages of these technologies have been discussed in Appendix: E). In order to achieve this, a practical approach is required to compare the selected cutting technologies. Therefore these cutting technologies will be tested in simulated environment to compare their performance in ship recycling yard

7.5 Selection and introduction of case study blocks

For this study, two different blocks that can be commonly found from the selected ships.

- Block from accommodation area
- Double bottom block

7.5.1 Block from accommodation area

One of the selected blocks (Figure 7.2) was from the accommodation area of the ship and selected in this case study as it was very similar to the data collection block. It was assumed that all the insulation materials, outfitting and cables were removed during the pre-cleaning stage.

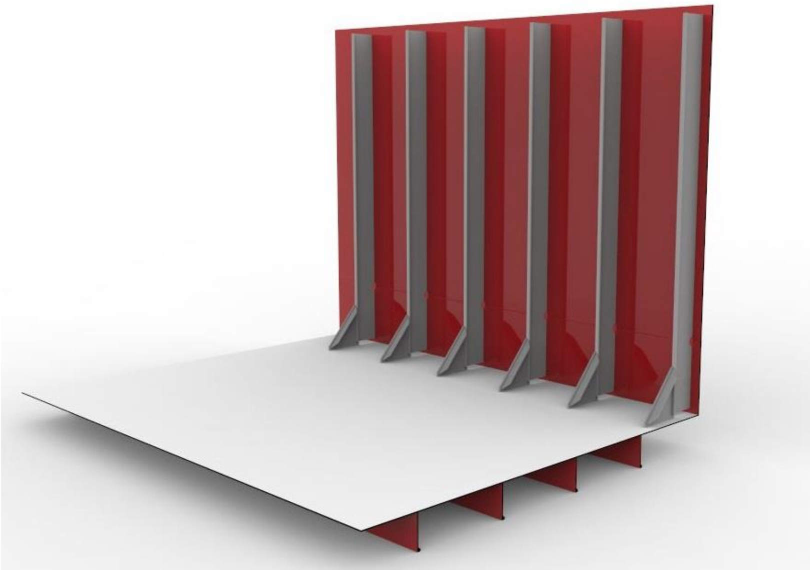


Figure 7.2: Accommodation area block

The selected block consists of two main parts: vertical and horizontal plates. The thickness of both plates is uniform throughout the plate, and it is 10 millimetres. The dimensions of the bottom plate are 3,500 by 2,700 millimetres. The vertical plate is 2,700 millimetres in height and 3,500 millimetres in length. Both plates have strength elements with 150 millimetres height and 10 millimetres thickness (Figure 7.3). The weight of the block is approximately 2.8 tons.

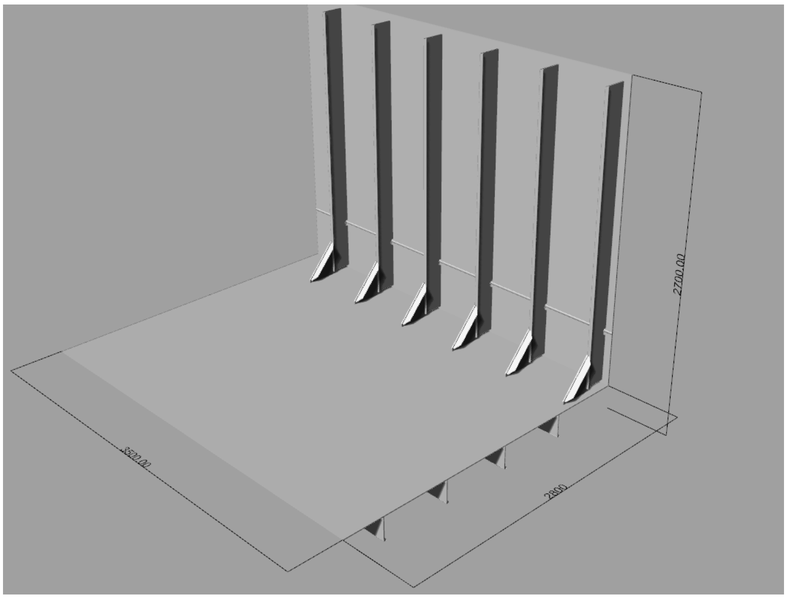


Figure 7.3: Dimensions of the accommodation area block

Cutting lines and the distances were summarised in Appendix D. During the calculation of the cut lines, yard's current application on the maximum plate dimension was followed (1metre x 1 metre). Yard follows these dimensions according to the steel scrap factories and their requirements.

7.5.2 Double-bottom block

The second type of block selected was a double bottom block (Figure 7.4), which might be covered with oil and chemical residues, which creates a high risk of fire during cutting operations.

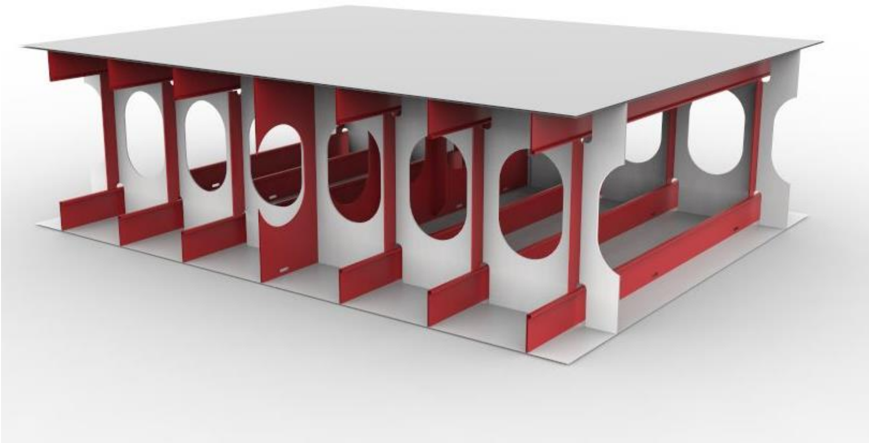


Figure 7.4: Double bottom block

The double bottom block consists two horizontal and three vertical plates. Vertical plates are strong elements, and both horizontal and vertical plates are supported with stiffeners. Also, to give access to the double bottom and to decrease weight, vertical plates have manholes through their length. The overall dimensions of the block are 4,150 millimetres in length, 3,350 millimetres in width and 1,250 millimetres in height (Figure 7.5). The steel thickness of the block is uniform through the block, and it is 15 millimetres.

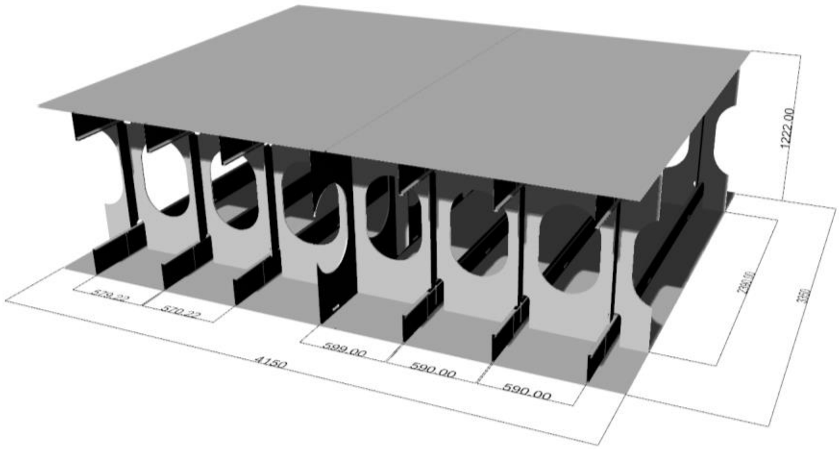


Figure 7.5: Dimensions of the accommodation area block

7.6 Translation of the Model to Arena and Validation through the Data Collection Block

The ARENA model created for this study was introduced in this section. In order to simplify the modelling, sub-model were used in the models. A generic model was developed first for all blocks.

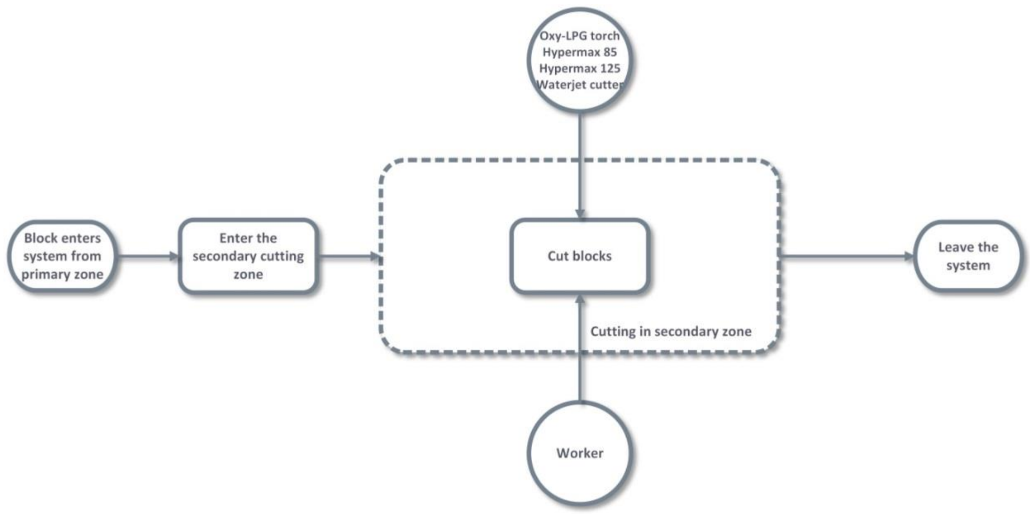


Figure 7.6: Simplified representation of the generic model for no surface treatment case

In the simplified representation of the generic model shown in Figure 7.6, block entered the simulation system from the primary cutting zone and transferred to the secondary cutting zone. In the secondary zone, the block is cut into smaller pieces for the transport then leaves the system. This model applies to all case blocks (for no surface treatment case) as long as the module named “Cut Blocks” is designed as sub-model and altered for all blocks according to the cutting lines. In this model, resources allocated is the worker who will conduct the cutting and depending on the scenario, oxy-LPG torch, Hypermax 85/125 plasma or waterjet cutter.

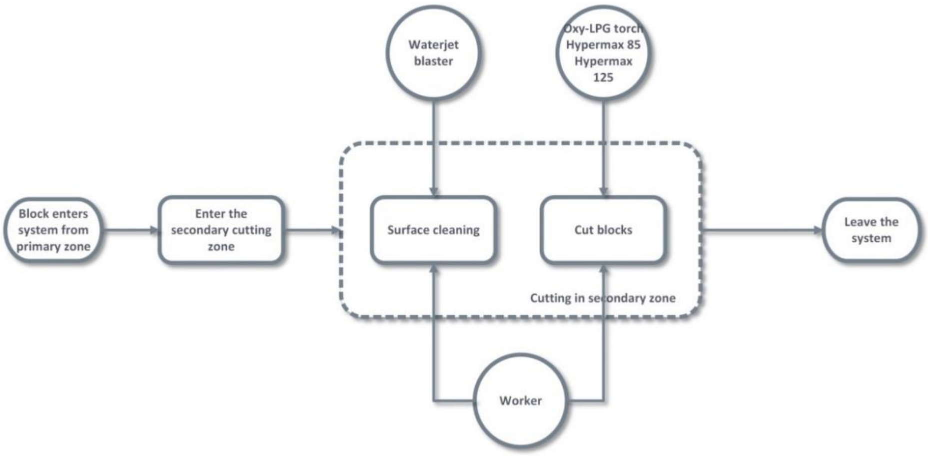


Figure 7.7: Simplified representation of the generic model for surface treatment case

The second model in Figure 7.7 represents the cases with surface cleaning. Similar to the model in Figure 7.6, block enters the simulation system from the primary cutting zone, transferred to the secondary cutting zone and in the secondary zone surface of the block is cleaned with waterjet blasting method before it is cut to smaller pieces. Then block leaves the system. This model is also applicable to all case blocks for surface treatment case but “surface cleaning” and “Cut Blocks” should be adjusted according to the cutting lines. In this model, resources allocated is the worker who will conduct the cutting and depending on the scenario, oxy-LPG torch, Hypermax 85/125 plasma or waterjet cutter.

The above models were created in the ARENA simulation environment next. In the generic model shown in Figure 7.8, block enters the simulation system through the CREATE module, goes through the data modules, “Record incoming block” (RECORD) and “Assign time and picture” (ASSIGN), and enters the “secondary cutting” zone (STATION). In the “Cutting in secondary zone module” (SUBMODEL), cutting operation is conducted, and the block leaves the system through “Record outputs” (RECORD) and “Dispose” modules.

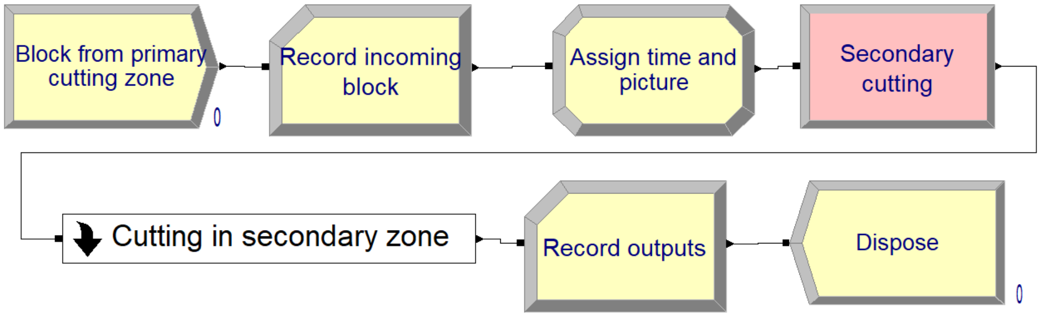


Figure 7.8: Generic model for the cutting simulation

Block from the primary cutting zone (CREATE): This module creates only one entity for this simulation. In this case, this entity was accepted as the block.

Record incoming block (RECORD): This module records the entities coming into the simulation system. This block is for statistical purposes only.

Assign time and picture (ASSIGN): This module assigns arrival time and a picture to the block.

Secondary cutting (STATION): These modules show the route of the block in the shipyard.

Cutting in secondary zone submodel: This submodel was used to prevent complexity in the primary model. As mentioned before, the cutting process of the blocks was modelled in this submodel. Contents and the flow of this submodel differ for each block.

Record outputs (RECORD): This module records the number of the pieces leaving the system

Dispose (Dispose): Entity (block) leaves the system/yard.

Moreover, a second model (Figure 7.9) for the surface cleaning case was also designed. The main difference in this block is the Surface cleaning submodel which involves the surface preparation before the cutting operation.

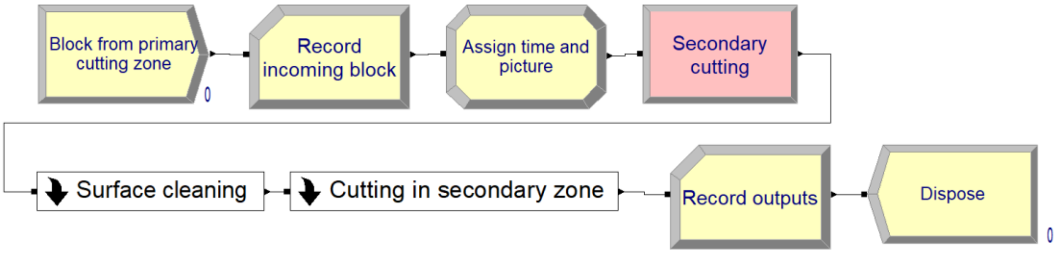


Figure 7.9: ARENA model for the surface cleaning and cutting with Oxy-LPG/Plasma operation

7.6.1 Accommodation Block

As mentioned before, the accommodation block was one of the two blocks selected for this study. The initial assumption for the dismantling of this block was that all the insulations, outfitting elements, cables etc. were removed from the block. The only operation to be conducted on this block was to cut it into smaller pieces to comply with the requirements of the steel milling company selected. The dimensions of this block were 3,500 – 2,800 – 2,500 mm.

During the dismantling of this selected block, the block was first divided into two pieces for more comfortable operation. These two pieces were cut into pieces that are 0.9 meters in length and 0.9-meter width. Even though the smelter accepts steel plates up to 1.0 meter to 1.0 meter, 10% safety factor was added to cutting plans to mitigate any errors while cutting.

Two different scenarios were considered for the block; no surface cleaning required, and surface cleaning of the block. For the first scenario, it was assumed that no surface cleaning required to be conducted and only cutting operation was conducted. Three different cutting alternatives, Oxy-LPG torch, plasma, and waterjet cutting were considered for this scenario.

In the submodel (namely "Cutting in the secondary zone") simulates the splitting of the horizontal/vertical sides of the block and then the cutting of these blocks to smaller pieces. In total 65, cutting lines were decided for this block; 7 for dividing the block into aforementioned two pieces, 29 for the horizontal part and 29 for the vertical part.

The same model with the Oxy-LPG torch (Figure 7.8) was used for the cutting with plasma simulation. The main change for this simulation was the machine preparation times and process times for each cut. Cutting speeds from the manufacturer's data sheet were used to estimate the duration of each cutting line and a second for piercing time were added to the durations as suggested by the manufacturer.

In addition to the plasma, abrasive waterjet cutters are the other alternatives to oxy-fuel cutting. The main difference (and challenge) of the waterjet model is that the waterjet cutter needs to be set up for each cutting line. Therefore, the setup phase needs to be represented in the model. In order to represent the setup, set-up delays were added to the model (instead of the repositioning delays in the worker case).

As a second scenario, it was assumed that the surface cleaning operation was required to be conducted due to the toxic paint on the surface. Therefore, the different cutting alternatives were combined with surface cleaning and simulated; surface cleaning (waterjet) and cutting with Oxy-LPG torch, surface cleaning(waterjet) and cutting with plasma. In the next sections, details and results of these simulations are presented.

Surface cleaning submodel (Figure 7.9) represents the surface preparation before the cutting operation to split the blocks. Surface preparation data was collected from the shipyard; it was accepted that $0.2m^2$ could be cleaned using the waterjet and the duration used in the model were found from the extrapolation of this data according to the cleaning area. Details can be found in Appendix D.

7.6.2 Double Bottom Block

In this block, the initial assumption was the block was covered with flammable oil residues. Therefore, surface cleaning was required. The surface cleaning scenario was included in the simulation for the dismantling of this block, and it as assumed to be stripped entirely clean from the residues. The surface cleaning scenario was then combined with two different cutting alternatives Oxy-LPG and Plasma.

In this model (Figure 7.8), all the cleaning operation was modelled in the Surface cleaning submodel. Cutting in secondary submodel split the top half and the bottom half of the double bottom (also separate module splits the entity (block) into two entities) and deals with the cutting operation for further dismantling.

7.7 Data Collection on Production Performance

Comprehensive data collection campaigns and field studies have been conducted as part of this PhD study. The approach adopted for data collection was given in Section 4.2. In this section, data collected through previously explained (Section 4.2) time-motion study is demonstrated and utilised in simulation scenarios. Apart from the data obtained through the time-motion study, manufacturer's performance data was also utilised.

In following sections, performance data collected for each cutting technology are summarised.

7.7.1 Oxy-Fuel Cutting

For oxy-fuel cutting technology, two different sources of data have been obtained; (1) operational data from the yard, (2) manufacturer performance data of the oxy-fuel torch.

7.7.1.1 Oxy-Fuel Cutting Actual Operation Data

In order to collect the needed data on oxy-fuel cutting, a field study was conducted in the ship recycling yard. The full recycling of a block was observed during this field study, which starts from cutting on board the end of life vessel and ends with the transport of the block out of the yard.

The selected block (Figure 7.10), is a very common type of block on the ship and observation on this block considered sufficient for the purpose. The selected block was located in the accommodation area of the ship and dimensions of the block are given below;

- Width: 3.0 m
- Height: 2.0 m
- Length: 3.5 m
- the thickness of the steel: 15 mm and
- the height of the stiffeners: 0.1 m.

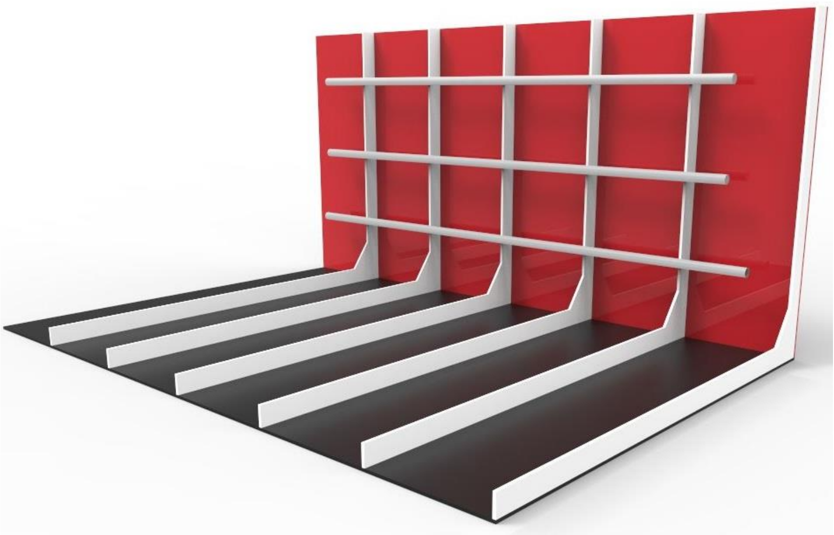


Figure 7.10: Selected block for data collection study.

The process of the dismantling of this block is shown in Figure 7.11.

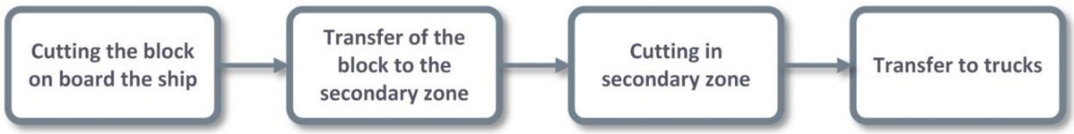


Figure 7.11: Dismantling process for the data collection study

Initially, the panel section is cut from the ship with oxy-fuel (acetylene) cutting. One cutter and one helper conducted this step. The overall time of this procedure was recorded as 22 minutes. Once this step is complete, the block is transferred to the secondary cutting zone of the yard using crane and truck. The transfer process to the secondary zone took 6.30 minutes in total. After the transfer, a cutter and a helper conducted the further cutting in the secondary zone which took 61:34 minutes Total cutting time (torch time) recorded is 55:58 minutes, the difference in the timing is the repositioning of the worker. Cut lines are shown in Figure 7.12.

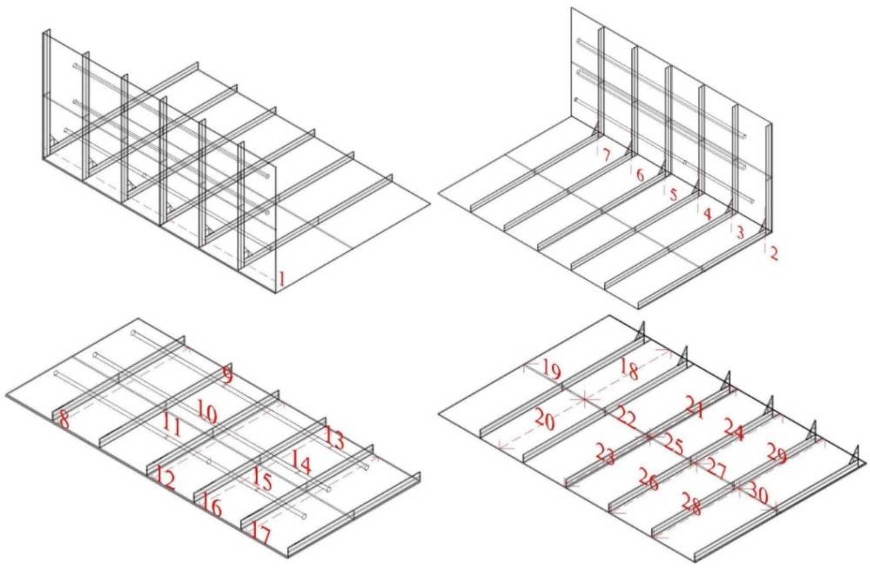


Figure 7.12: The cut lines

The duration of each cut was recorded to use in the simulation step of this study. The detailed timings are given in Table 7.2.

Table 7.2: Duration of each cut number for the selected block

Type of cut	Cutline #	Distance cut(m)	Total time (min)	Preheat and pierce duration (min)	Cutting time (min)
Plate	Cutline 1	3.75	07:30	00:20	07:10
Profile	Cutline 2	0.3	01:02	00:12	00:50
Profile	Cutline 3	0.3	00:59	00:14	00:45
Profile	Cutline 4	0.3	01:02	00:10	00:52
Profile	Cutline 5	0.3	01:04	00:09	00:55
Profile	Cutline 6	0.3	01:32	00:12	01:20
Profile	Cutline 7	0.3	01:06	00:16	00:50
Plate	Cutline 8	1.75	02:53	00:09	02:44
Pipe	Cutline 9	0.1	00:09	00:05	00:04
Pipe	Cutline 10	0.1	00:25	00:15	00:10
Pipe	Cutline 11	0.1	00:16	00:09	00:07
Plate	Cutline 12	1.75	02:53	00:11	02:42
Pipe	Cutline 13	0.1	00:18	00:10	00:08
Pipe	Cutline 14	0.1	00:21	00:08	00:13
Pipe	Cutline 15	0.1	00:17	00:10	00:07
Plate	Cutline 16	1.75	02:55	00:20	02:28

Type of cut	Cutline #	Distance cut(m)	Total time (min)	Preheat and pierce duration (min)	Cutting time (min)
Plate	Cutline 17	1.75	02:54	00:15	02:24
Plate	Cutline 18	1.25	02:26	00:20	02:06
Plate	Cutline 19	1	01:54	00:19	01:32
Plate	Cutline 20	1.25	02:05	00:17	01:48
Plate	Cutline 21	1.25	02:25	00:20	02:05
Plate	Cutline 22	1.03	01:58	00:15	01:43
Plate	Cutline 23	1.25	02:07	00:17	01:50
Plate	Cutline 24	1.25	03:00	00:24	02:36
Plate	Cutline 25	0.82	01:31	00:15	01:16
Plate	Cutline 26	1.25	02:26	00:15	02:11
Plate	Cutline 27	0.72	01:20	00:28	01:05
Plate	Cutline 28	1.25	02:28	00:15	02:13
Plate	Cutline 29	1.25	02:30	00:10	02:20
Plate	Cutline 30	0.72	01:35	00:18	01:17
		TOTAL	**55:58**		
	TOTAL OPERATION TIME		**61:34**		

When analysed further, the average cutting speed of the torch during horizontal cutting is calculated 600 mm per minute. In order to do this analysis, preheat and piercing times were deducted from the total cutting time and actual cutting time was found (Table 7.2). Then the cutting time divided by the cutting distance to find the average cutting speed per minute. Moreover, during the vertical cutting, the average cutting speed of the worker is 300 mm per minute. The difference in the speed reduction is due to the positioning of the torch and the worker. During the simulation, the effect of the worker's positioning is also taken into account by decreasing the production rate by 50% similar to the worker's performance in data collection study.

7.7.1.2 Oxy-Fuel Cutting Manufacturer Data

In addition to the operational data, manufacturer data of the torch (and the nozzle) used in the yard is also collected. This data will help us understanding whether the manufacturer data can be used instead of the operation data for alternative cutting methods. Therefore, the performance of the worker and the manufacturer data will be compared to the simulation.

Table 7.3: Manufacturer production data of the torch nozzle for oxy-LPG cutting

Metal Thickness	Pressure kg/cm2		Consumption Nl/hr			Cutting speed
mm	**oxygen**	**fuel gas**	**cutting oxygen**	**preheat oxygen**	**fuel gas**	**mm/min**
5	7.0	0.2	750	1180	310	750
5-10	7.0	0.2	1100	1180	310	750-680
10-15	7.0	0.2	2500	1180	310	680-600
15-30	7.0	0.25	3800	1370	360	600-500
30-40	7.0	0.25	5400	1370	360	500-450
40-50	7.0	0.3	7300	1860	490	450-400

When compared with the cutting speed of the worker, it can be seen that the cutting speed of nozzle for 15 mm metal thickness is the same, 600mm/min. Therefore, it is consistent with the initial idea of using the manufacturer data instead of operation data.

7.7.2 Plasma cutting

In order to compare the current oxy-LPG cutting method with the plasma cutting, portable plasma cutting systems were investigated in detail. Interviews with OEM’s and ship recyclers were conducted to find the most suitable plasma cutting kit for the ship recycling operations. For this operation, two different plasma cutting kit was selected. One of the kits, Powermax 125, is for general use in the ship recycling yard to cover all the thickness range in the recycling yard, and another kit, Powermax 85 specifically selected for the steel thickness of the block (Hypertherm, 2017a, Hypertherm, 2017b).

Production operation tables for both options were given in Table 7.4. Production speeds are approximately 80% of maximum cut speed (hypertherm.com, 2017).

Table 7.4: Production operation table for Powermax 85 and Powermax 125 (Hypertherm, 2017a, Hypertherm, 2017b)

Powermax 85			
Material Thickness (mm)	Pierce Delay (sec)	Cut speed for best quality (mm/min)	Cut speed for production (mm/min)
3	0.1	6800	9200
4	0.2	5650	7300
6	0.5	3600	4400
8	0.5	2500	3100
10	0.5	1680	2070
12	0.7	1280	1600
16	1.0	870	930
20	1.5	570	680
Powermax 125			
Material Thickness (mm)	Pierce Delay (sec)	Cut speed for best quality (mm/min)	Cut speed for production (mm/min)
6	0.2	4980	5960
8	0.3	3800	4570
10	0.4	2750	3330
12	0.5	2050	2510
16	0.6	1260	1660
20	2.0	980	1140
25	3.5	610	780

7.7.3 Water jet cutting

Waterjet will be specifically tested for the double bottom block, where the risk of explosion and fire risk are very high due to the explosive gasses and contaminated surfaces with fuel and oil. Waterjet cutting systems are mostly fixed systems. However, mobile systems are also available as mentioned in 0. The production data for a mobile waterjet cutter is taken from DIVEST project's state of the art report (DIVEST, 2009a).

Table 7.5: Production rate for the abrasive waterjet cutter (Modified from DIVEST (2009))

Thickness (Inch)	Thickness (mm)	Production rate (inch/min)	Production rate (mm/min)
0.25	6.35	25.8	655.32
0.375	9.525	16.1	408.94
0.5	12.7	11.6	294.64
0.75	19.05	7.2	182.88
1	25.4	5.2	132.08
1.5	38.1	3.3	83.82
2	50.8	2.4	60.96

7.8 Validation of model through the Data Collection Block

Data collection block was first modelled in ARENA software to verify the ARENA model. In order to verify the model, first, observational data was used as the input in the ARENA. Total operation time observed during the data collection and the total operation time from the simulation (using the observational data) are same which shows that the model works correctly.

Next, the manufacturer data on the cutting speed of the torches, for the given thickness, was used as the input to the simulation to verify that manufacturer data can be used instead of a worker's performance data for the cutting operations (The data used for each cutting line are shown in Appendix D). Moreover, instead of the actual observed data for each repositioning, the distribution of the observed repositioning times was used in the model (Appendix D). The difference between the actual performance data and simulation is less than 2% (Figure 7.13). Therefore, it was concluded that manufacturer's data can be used with acceptable error margin when compared to the actual data collected.

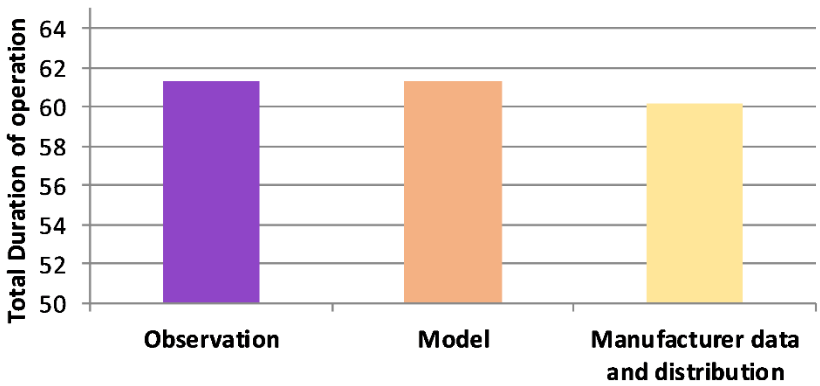


Figure 7.13: Results of the validation simulation

7.9 Interpretation of the Results

In this section, results of the ARENA simulation were given and discussed.

7.9.1 Accommodation Area Block

The simulation for the accommodation area block was run for ten replications. Given in Table 7.6 and Figure 7.14 is the average duration of each option for the dismantling operation.

Table 7.6: Duration of the operation for different process options

	Oxy-LPG manufacturer data(min)	Powermax 85	Powermax 125	Waterjet (min)	Surface Cleaning & Oxy-LPG Cutting (min)	Surface Cleaning & Powermax 85 (min)	Surface Cleaning & Powermax 125 (min)
Surface cleaning duration	-	-	-	-	62:55	62:45	63:07
Cutting duration	60:36+47:23	34:18+29:00	23:26+20:11	129:55+121:59	60:08+44:51	35:58+27:47	25:06+18:46
Total duration	107:59	63:18	43:37	251:54	167:54	126:40	106:59
Cost	€33.07	€26.09	€20.17	€96.13	€55.52	€46.89	€43.72

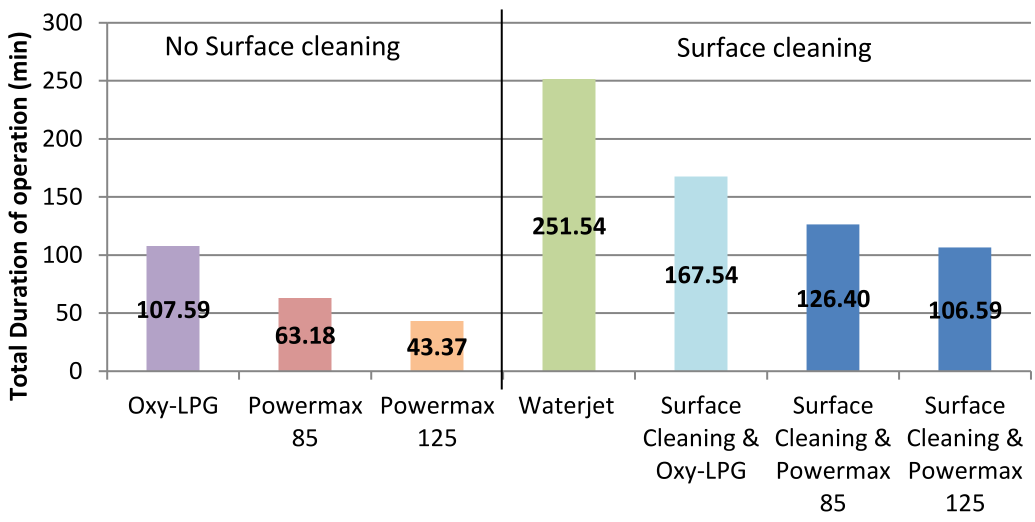


Figure 7.14: Comparison of the operation durations for different technologies during the dismantling process

Simulation results demonstrates that dismantling of the block using plasma (both options) is much faster compared to oxy-LPG (Figure 7.14). Even for a small operation like this, dismantling time is approximately 60% faster compared to Oxy-LPG and 80% faster compared to abrasive waterjet cutting.

It can be said that replacing the oxy-fuel with plasma cutters can increase the productivity in the cutting operation.

Moreover, even though the running cost of the plasma is more than the twice of the oxy-LPG's running cost, this operation is slightly cheaper with (€20.17 & € 26.09) plasma than oxy-LPG (€33.07) due to the reduction in the operation time (Figure 7.15). Powermax 125 model was selected to be able to operate on all the thicknesses of metals that the yard might come across, while Powermax 85 model was the selection to cover the thickness of this block specifically. In theory, it was thought that Powermax 125 would be the excessive choice for this operation due to the over-consumption of resources (gas and electricity) for the given metal thickness. However, even though the running costs of the Powermax 125 is higher compared to 85 model, the overall operation cost is lower for 125 model combined with the worker costs. This advantage is due to the higher cutting speed achieved in this model for the given thickness which lowers the overall operation time hence the use of worker's time.

When the surface cleaning is involved, both the total time and cost of the operation increases by more than 50% for oxy-LPG cutting. However, even without the surface treatment, waterjet is still not a viable option due to the high operation cost, slow cutting speed and the time required to set up for each case.

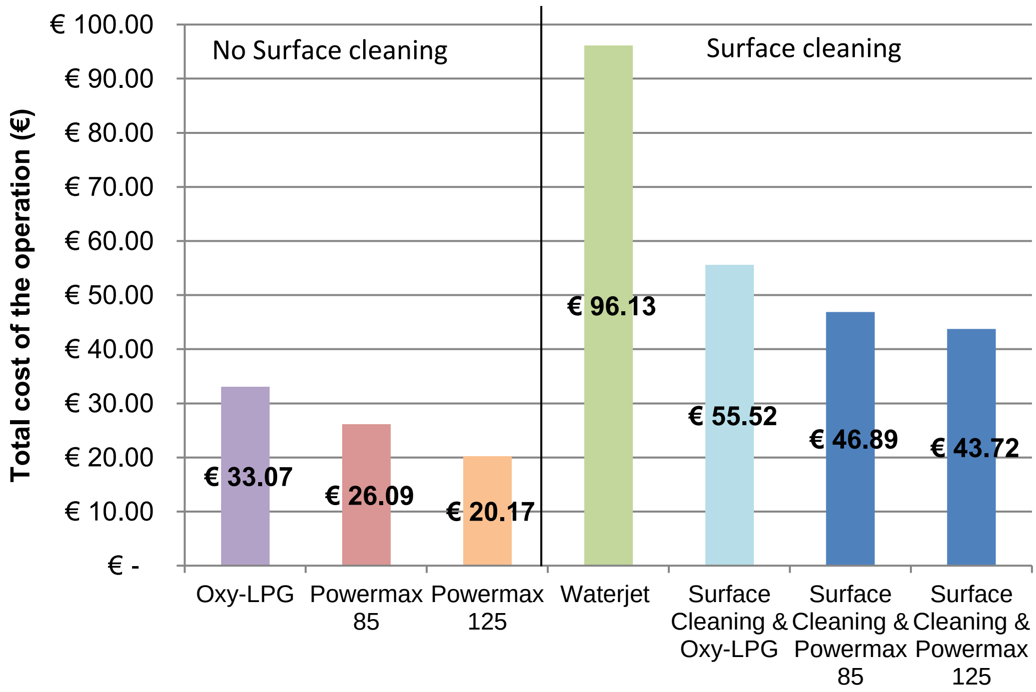


Figure 7.15: Comparison of the total cost of the operation (€)

When the simulation is run for a whole workday, a worker can dismantle four of the blocks in this specific case using oxy-fuel cutting (Figure 7.16). However, the same number can be achieved almost in half a work day (04:16:47) using the Powermax 85 and almost three (02:51:29) hours with Powermax 125. Moreover, after a full work day, seven (and the horizontal part of the last block) of this block can be entirely dismantled with Powermax 85 and 11 with Powermax 125.

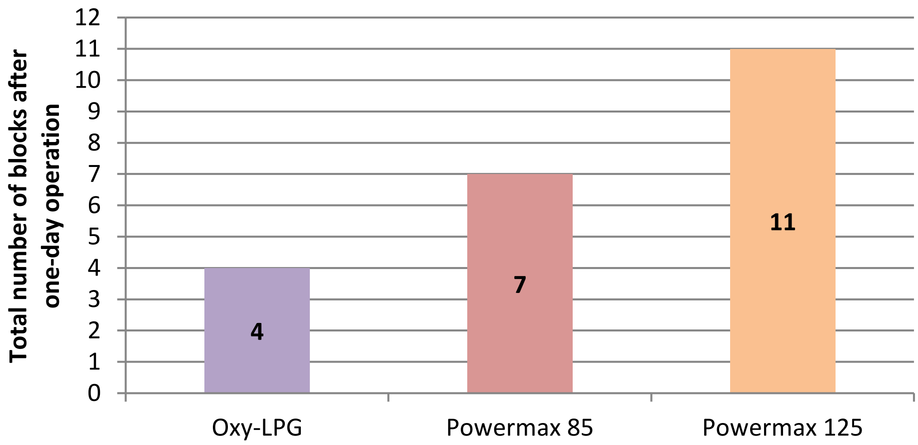


Figure 7.16: Total number of block dismantled if the operation was run through an eight-hour shift.

The operational cost of running this equipment for the eight-hour shift was also given in Figure 7.17. Oxy-LPG's operation cost is €147 and lowest for the all-day shift, but the four blocks that could generate the revenue around €3k (scrap steel ton price was taken as €270 from Bimel Metal (2018)). The revenue given in Figure 7.18 is theoretical and calculated directly through the total weight and the price per ton of scrap steel. In order to find the right revenue and profit, the costs associated with the operation, costs such as overhead, upkeep, maintenance, financial (banks and interests) and overall management costs of the ship recycling yard should also be taken into account.

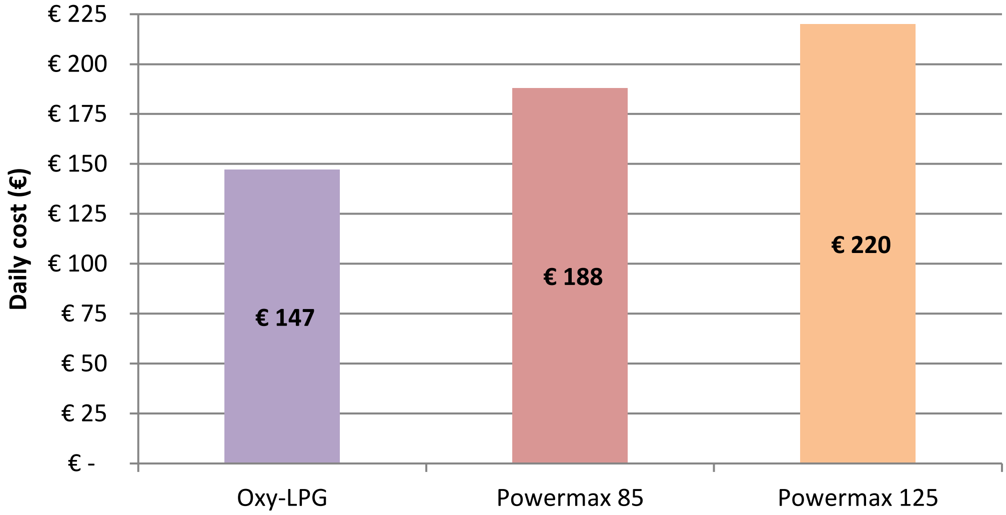


Figure 7.17: Total operation cost for an eight-hour shift

Powermax 125, with the highest cost of €220 for daily operation, generates the revenue around €8.3k per working day (Figure 7.18); therefore, based on the eight-hour shift simulation, Powermax 125 is a better option on the economic perspective for the selected accommodation area block.

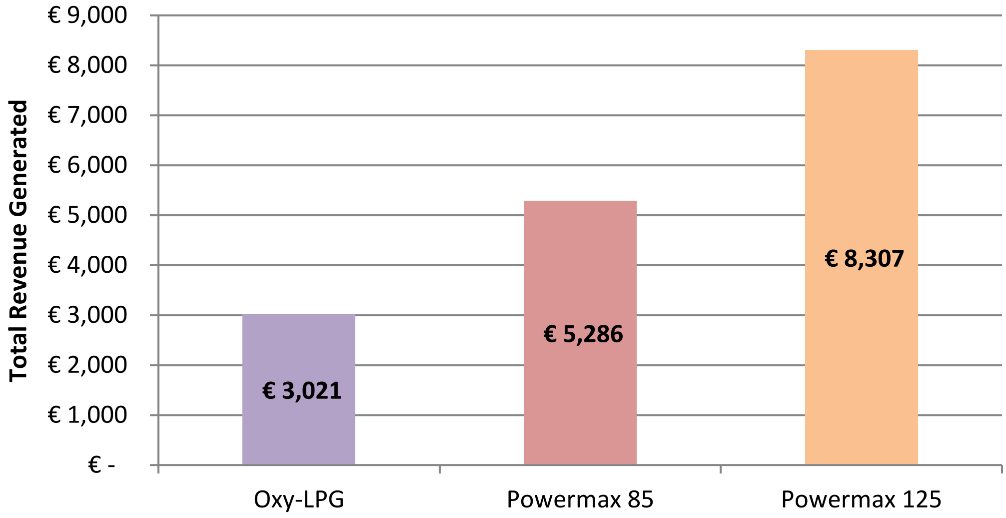


Figure 7.18: Theoretical revenue for an eight-hour shift

7.9.2 Double Bottom Block

Similar to the accommodation block; the simulation of the double bottom block dismantling was also run for ten replications. The comparison of the options is given in Table 7.7.

Table 7.7: Duration of the operation for different process options

	Waterjet (min)	Surface Cleaning & Oxy-LPG Cutting (min)	Surface Cleaning & Powermax 85 (min)	Surface Cleaning & Powermax 125 (min)
Surface cleaning duration	-	373:18	366:45	376:16
Cutting duration	283:16+220:43	112:21+96:55	60:10+55:28	46:30+39:21
Total duration	503:59	582:34	492:23	452:36
Cost	€221.20	€220.45	€206.66	€195.54

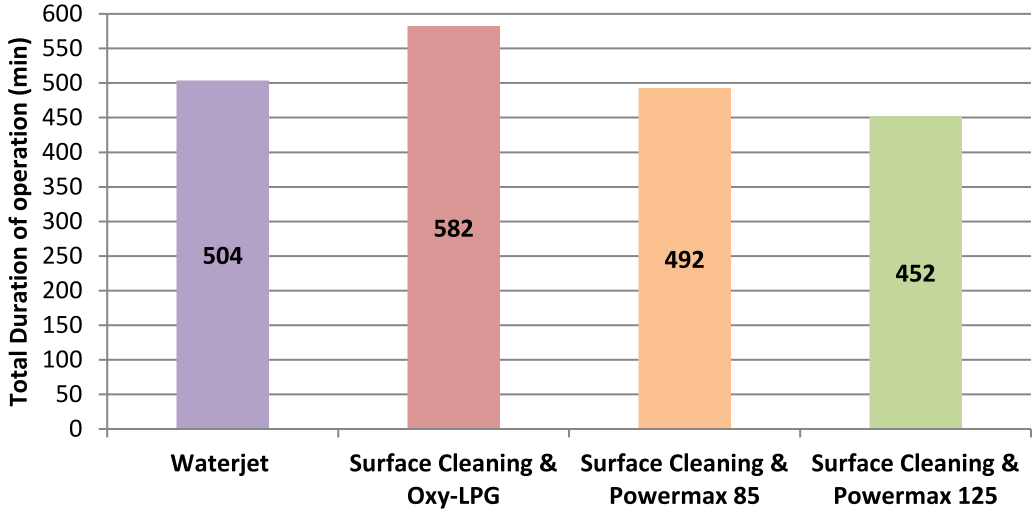


Figure 7.19: Total operation time for double bottom block dismantling

The economic performance of the oxy-fuel and waterjet are similar (Figure 7.20) in the double bottom scenario (€221.20 & €220.45), but waterjet is a faster alternative (503:59 min & 582:34 min) when the production performance is considered (Figure 7.19). Similar to the accommodation case, plasma cutting scenarios are again the best options for this operation.

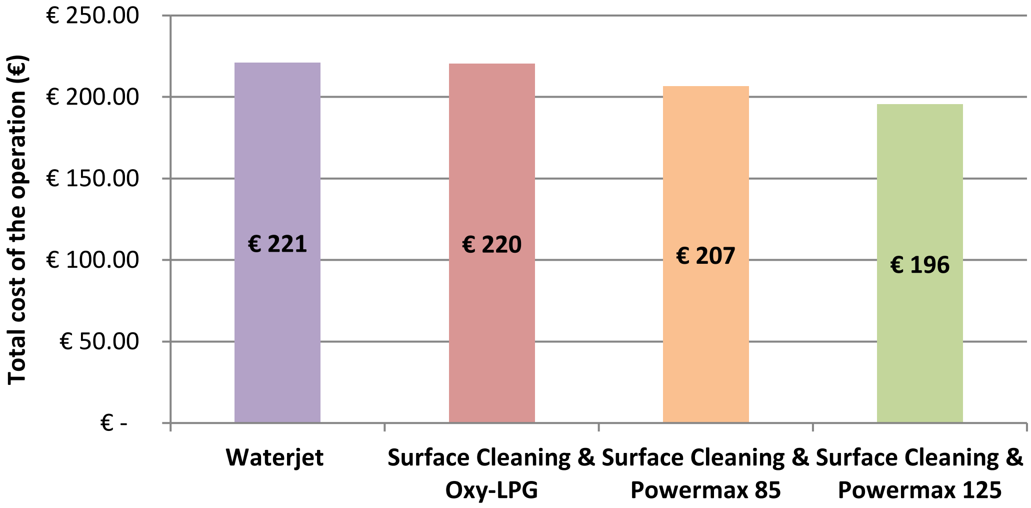


Figure 7.20: Total cost of the operation

In the ship recycling yards, surface treatment case is not a very common practice due to the cost and the time loss. Both case studies also show that the surface creates additional cost and increases the time considerably.

7.10 Decision: What is the Best Cutting Option for Ship Recycling?

Results of this study show that plasma cutting is a viable alternative to commonly used oxy-fuel cutting for the daily metal cutting tasks in the yard. Plasma cutting can provide around 60% improvement in the productivity of the primary and secondary dismantling zones of the ship recycling yards. Even though the initial and consumable costs of the plasma cutting is more expensive compared to the oxy-fuel cutting, plasma cutting is superior to the oxy-fuel (LPG in this specific case). The capital expense (CAPEX) of the plasma cutting is around €10,000 that is high compared to the €300 investment cost of the oxyfuel cutter. Moreover, on the operation expense (OPEX) perspective, oxy-fuel cutting (€21/hour total operation cost) is also much cheaper compared to advantages plasma cutting (€33/hour) (Details on capital and operation costs can be found in Appendix D). However, using plasma cutting, the difference in CAPEX and OPEX can be compensated due to the high performance, which compensates through the lower operation time, lower worker cost and higher throughput of the yard. One of the causes for performance difference is the fact that the oxy-fuel requires the metal to be preheated before cutting, while plasma does not have this requirement. This also improves the quality of the steel as there is minimal slag on the cut edges. Even though it is generally not crucial for ship recycling, sometimes plates are sold as it is for direct reuse if they are in good condition. Plasma torches can cut non-ferrous metals and stainless steels while oxy-fuel torches cannot. This is important for the ship recycling business as some ships contains stainless steel parts (equipment, pipes, cargo holds, and so forth), as well as aluminium or cast iron parts. Plasma torches can operate on these metals without any loss of productivity.

On the other hand, oxy-fuel torches allow better portability and mobility compared to the plasma. Even though the modern plasma systems are lighter and longer torch and connection options are available, they still require an electrical connection and compressed air source. Oxy-fuel cutters only require the torch and hose from the gas source to be operated. Plasma cutters can also achieve the similar portability, but it requires further investment by the yard for electricity connection point and additional compressed air sources.

The initial investment cost of a handheld plasma machine is more expensive compared to oxy-LPG torch system. An appropriate plasma cutting machinery for ship recycling with the torch equipment cost varies around €5,000 to €10,000 depending on the maximum cutting capacity and torch length (cable), and consumables and replacements tips cost about €10 to €40 depending on the size (Lincolnelectric.com, 2017a, Weldersupply.com, 2017, Lincolnelectric.com, 2017b) (Details can be found in Appendix D). On the other hand, oxy-fuel cutting equipment costs around €300 and €1500 and the cutting tips costs between €10 and €20. Also, there is always the cost of the oxygen and fuel costs and maintenance of the cylinders for safety. Additionally, there must be additional storage for the storage of these tanks separate from any source of fire, ignition or spark.

Waterjet cutters on the other hand were not found to be a feasible option for the industry due to the slow production rate, high investment cost and the time required for the setup. Waterjet cutting has their advantages, especially in the areas where hot cutting is dangerous. Advantages of waterjet over plasma cutting and oxy-fuel cutting include: Operation at much lower temperatures thus no surface preparation is required if the part is contaminated with flammables, can cut a vast range of materials, both metal and non-metallic. Therefore, if the improvements in the technology are achieved, they can become a feasible option for the ship recycling industry.

All these three technologies have their benefits and shortcomings and deciding which technology to use depends on factors such as material type to cut, metal thickness, available power resources, cost and location of the job.

7.11 Implementation of Plasma Cutting Technology for Further Optimisation

The study in this thesis showed that the plasma cutting is a viable option for ship recycling industry and can save up to 40-60% in the operation time depending on the operation type. In this section, Plasma cutting will be applied to ship recycling operations in the designed yard in Chapter 6 and the effect of this modification in the big scale will be investigated. The reduction in the operation time in the secondary dismantling zone is reflected to the overall block dismantling time by 50% as achieved earlier in this section.

In order to compare the plasma cutting scenario to the existing alternatives, process analyser of the Arena is used. The Process Analyzer mode of Arena assists the analyst and decision makers during the evaluation of alternatives. The Process Analyzer executes different simulation model scenarios using the inputs provided. The Process Analyzer allows comparison of the outputs with given criteria and only focuses the post-model development comparison of models, hence, it is important to complete, validate and configure the models to use in the Process Analyzer. Criteria can be introduced to the system as “Controls” which are defined as the inputs that are considered to affect the operation in a manner that can be monitored/viewed in the output of the model Figure 7.21.

	Scenario Properties				Controls								
	S	Name	Program File	Reps	Crane	Polygrab	Secondary cutting zone slot	Torch	Total foreman	Total operators	Total workers	Num Reps	Rep Length
1		1	5 : final sim.p	100	1.0000	1.0000	35.0000	30.0000	1.0000	1.0000	6.0000	100	Infinite
2		2	5 : final sim.p	100	1.0000	1.0000	35.0000	30.0000	1.0000	1.0000	12.0000	100	Infinite
3		3	5 : final sim.p	100	1.0000	1.0000	35.0000	30.0000	1.0000	1.0000	18.0000	100	Infinite
4		4	5 : final sim.p	100	1.0000	1.0000	35.0000	30.0000	1.0000	1.0000	24.0000	100	Infinite
5		5	5 : final sim.p	100	1.0000	1.0000	35.0000	30.0000	1.0000	1.0000	30.0000	100	Infinite
6		6	5 : final sim.p	100	1.0000	1.0000	35.0000	36.0000	1.0000	1.0000	36.0000	100	Infinite
7		7	5 : final sim.p	100	1.0000	1.0000	35.0000	42.0000	1.0000	1.0000	42.0000	100	Infinite
8		8	5 : final sim.p	100	1.0000	1.0000	35.0000	48.0000	1.0000	1.0000	48.0000	100	Infinite

Figure 7.21: Scenarios and Controls in the Process Analyzer

Using the Process Analyzer, Oxy-fuel and Plasma cutting scenarios with different resource combinations. This analysis (plasma cutting scenario combined with the yard in Chapter 6) run for two different time frames. In the first time frame the simulation was run for a year period and in the second time frame simulation was run until the dismantling of the six ships are completed.

Initial analysis of the simulation demonstrates that dismantling operation in the yard can be finished much quicker compared to the oxy-fuel cutting. Implementing the plasma cutting technology increases the yard’s production rate by 25% and increases the yard’s annual output above 60,000 LDT. In the year-long scenario, the dismantling operation in the primary and secondary dismantling zones are completely finished, using 24 or more workers. Apart from the dismantling time, implementation of the plasma cutting in the secondary dismantling zone also reduces the cost of the operation in this scenario. In average, the new operation system costs around 5% less than compared to using oxyfuel cutting in the secondary cutting zone which can be increased by implementing the use of plasma cutters to the primary dismantling zone as well. Furthermore, the detailed analysis of the cost show that approximately 40% of the costs are related to idle cost of the resources. This means that even though the resources are in the system, they are waiting for a job to be allocated to them, hence they are underutilised. If this situation is considered from the perspective of the worker, this means that worker is waiting for a block to be cut or a material to be handled. Therefore, this points out that an improvement can be made in the material handling systems or resources in the yard. Currently, crane and polygrab are operated by a single person and the operator needs to switch to crane from polygrab (or vice-versa) when needed. Since both machineries are essential for the operation, one operator becomes a bottleneck in the system. Therefore, it might be beneficial to add an operator to the system and test for improvement. Using two operators decreases the operation time below the 6,024 hours from the 7,000 hours where the dismantling of the vessel. Using two operators for crane and polygrab also decreases the overall cost of the operation as the fast movement of blocks reduces the idle time and the idle cost of the resources. Also, it is required to evaluate the combination of all these resources to find “what is best?” for the yard. Even though Process analyzer is a useful tool for the case by case comparison, more structured approach is needed to compare higher number of cases.

In order to identify the ideal resource numbers (worker, polygrab, crane, transporter, foreman) OptQuest which is an optimization engine, that allows users to conduct sophisticated analysis techniques based on scatter search methodology. As a result, OptQuest helps identifying “what is best?” for this yard rather than the previously used “What if?” approach. OptQuest incorporates metaheuristics to guide its search algorithm which uses a form of adaptive memory to remember which solutions worked well before and recombines them into new, better solutions. In order to conduct the optimisation through OptQuest, optimisation problem (or objective) should be defined to the system first. In this experiment, two sets of objectives are set to evaluate the factors. Once the optimisation problem is set, OptQuest evaluates the statistical outputs. For this experiment two different objectives are set;

1- Best economical (cost) scenario
2- Best performance scenario

Following controls in Table 7.8 have been used to identify the best scenarios;

Table 7.8: Resource range for the optimisation

Resource	Low bound	Suggested	High bound
Crane	1	1	2
Foreman	1	1	2
Operator	1	1	2
Polygrab	1	1	2
Secondary cutting zone slot	24	36	48
Technical manager	1	1	1
Total transporter	2	5	10
Total workers	6	24	48

In order to identify the best economical scenario, 814 iterations were completed to find the economically feasible option whilst using the plasma cutter as the cutting technology. In order to achieve the best economic performance in terms of costs, 12 workers are ideal as it provides the minimum cost with six ships, however, using 12 workers fails to meet the criteria of dismantling 60,000 LDT annually even with the oxyfuel cutting. Increasing the worker number to 24 meets the dismantling criteria but it also increases the cost by 21% which increases the resource cost to €1,020,350 level. Considering the other resources, 1 cranes, 2 polygrabs and 2 operator yields the best result (€692,650 resource cost) in terms of economic performance (Table 7.9) as the extra polygrab and operator increase the material flow in the yard and decreases the waiting time.

Table 7.9: Optimal resource combination for best economic performance

Crane	Foreman	Operator	Worker	Polygrab	Transporters
1	1	2	12	2	8

In order to identify the best performance scenario, 734 iterations were completed to create the maximum throughput. In the oxy-fuel scenario, performance of the yard was similar after 24 workers, however, the implementation of plasma cutting changes this performance issue at 40 workers, yard reaches the maximum performance (4,500 hours operation time). Moreover, combining with the other resources, two cranes, two operators, two polygrabs and 10 transporters should be employed in the yard for maximum steel production. However, it is not a profitable option as the resource cost increases 40% to around €1,400,000 in this scenario. Therefore, it is required to combine these two scenarios to a find the optimal.

Table 7.10: Optimal resource combination for best production performance

Crane	Foreman	Operator	Worker	Polygrab	Transporters
2	1	2	40	2	10

Combining both scenarios, to achieve the maximum profit while keeping the costs to minimum level, two scenarios above (minimum cost objective and maximum production output) were combined. As a result, employing 24 worker is the better option as compared to 30, 36, 42, and 48 workers it yields the highest profit. Similar to oxy-fuel cutting, worker numbers above 30 increases the cost and profit per LDT decreases for the 60,000LDT dismantling operation. Considering the involvement of other resources, the operation to dismantle six ships is completed around 4,900 hours using single crane, two polgyrabs, two operators and 24 workers. Using this resource combination, it is envisaged that the yard can dismantle around 70,000LDT annually.

Table 7.11: Optimal resource combination for best production performance

Crane	Foreman	Operator	Worker	Polygrab	Transporters
1	1	2	24	2	10

7.12 Verification and Final Decision

The scenario of implementing a different technology in the yard presented that with the suitable modifications ship recycling yard can reach its goal for annual dismantling capacity in the long term. Normal operations of the yard can be conducted with 12 workers easily and the goal of 30,000 LDT can be met easily. However, if the yard wants to reach the 60,000 LDT level, 24 workers should be considered with extra polygrab and crane operator and a faster cutting technology other than oxy cutting. The final operation time with 24 workers is around 4908 hours (205 days), which is better than the goal of 251 working days and in the long term yard can exceed the expectation of 60,000 LDT and reach 70,000 LDT dismantling capacity

This section has further contributed to the ship recycling yard development case study in Chapter 6 to show the applicability of the ship recycling design and optimisation framework presented in this thesis. More analysis with wider options can be considered in the future to further improve the performance, reduce the cost and achieve a more competitive yard of the future. In the next section, an additional short case study will be presented to demonstrate an alternative use for the simulation in the dismantling operations. This case study can be considered as a supplementary analysis to the case study investigated in this Chapter.

This scenario demonstrated that the designed layout in Chapter 6 can be satisfactory to meet the annual dismantling goal with additional modifications such as the number of workers, implementation of more modern technologies to ship recycling yard. In terms of the yard’s production rate and operation costs, plasma cutting has more advantages compared to using oxyfuel torches for cutting operations. The analysis showed that using plasma cutting will significantly help the yard to reach its goals on doubling the capacity in the long term. For further optimisation, alternative approaches can also be considered with increasing the in yard transportation, higher capacity cranes, polygrabs or increasing the docking capacity using the simulation approach. Main aim of this Chapter was to demonstrate how simulation can be a powerful tool on the ship recycling yard design as well as the optimisation of the operation and improvement of the performance.

7.13 Supplementary Analysis

One of the problems identified in Chapter 4 was the size of the steel plates that are prepared in the secondary cutting zone. Steel mills have different requirements for the steel plate and the current practice of the yard was assumed 1 meter to 0.5 meters. However, different steel mills have different technical requirements (i.e. 1meter to 1 meter) but it was observed that their price per ton offer was lower than the other mills, therefore, yard might have the tendency to go with the smaller plates due to the offer price. On the other hand, cutting the scrap steel too small surely creates too many cuts, therefore increases the overall time, cost and the emission during the process. Bigger size of scrap steel can be considered and tested in simulation in order to see the real benefit and to see whether the difference in the offer between 1 meter and 0.5 meter scrap blocks should be compared with the extra expenses that the 0.5 meter cutting creates.

For this simulation, five different block groups were selected to model the dismantling operation; two blocks from bow, block from side, blocks from aft and block from double bottom of the ship.

In this model the theoretical cutting lines to dismantle the model were drawn and the dimensions of these cutting lines were recorded. These cutting lines were used to estimate the cutting times for each line and eventually the dismantling of each block.

After the simulation model is created and data collected were identified to the system as input, the model was run for 100 replications. In the current case of the yard, selected barge is dismantled around 300 hours, which is approximately 40 working days (For the workers, a schedule has been created where the working hours are 8.00-17.30 with one hour break during noon). In the current production, there are only three cutters and one operator who is responsible of both the polygrab and the crane. This creates two bottlenecks, secondary cutting zone and the loading into the trucks. Since the cutters are limited, once the parts are transferred to the secondary cutting zone, each block has an average waiting time of 40 hours as the cutting teams are focused to the block cutting in the primary cutting zone. In addition, polygrab operation is slow, dependant of the availability of truck and the crane operation has more priorities. Following recommendations can be made for the yard,

- Current cutting size of the scrap steel is too small and creates too many cuts, therefore increases the overall time. Bigger size of scrap steel such as 1 meter in all lengths for transport can be considered. The difference in the offer between 1 meter and 0.5 meter scrap blocks should be compared with the extra expenses that the 0.5 meter cutting creates.
- Number of cutting teams should be increased in order to avoid the queueing problems in the secondary zone.

As a next step, the recommendations discussed above were applied to the current model. As a first step, the cutting size of the scrap steel was changed. When the plate size is increased to 1 meter (new case) from 0.5 meters (current case), the overall dismantling time of the barge reduces to approximately 210 hours (Figure 7.22). The decrease in the time for the new case is important, however, the most important difference is in the use of torch, which is around 50% lower compared to the current case. This means, the new operation generates 105 kg less CO_2 compared to the initial case (Considering that the 1kg of LPG burnt generates 3.023 kg of CO_2 (Deshpande et al., 2013b)). Only disadvantage of the bigger pieces is that the some mills offer lower price per ton for this scenario, however, this can also be neglected as in this case the overall reduction in the production time balances the loss due to the low offer per ton.

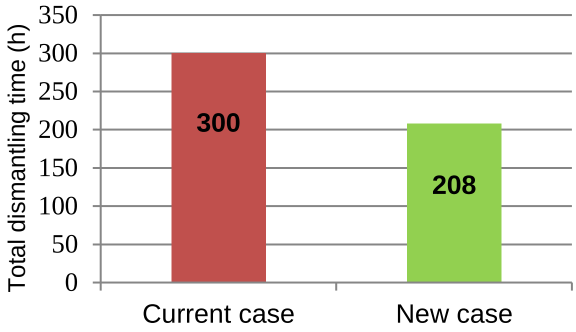


Figure 7.22: Comparison of production time for different scrap steel sizes

Secondly, the number of cutters were increased to five as previously planned by the yard. Increasing the number of the workers shortens the production time to 192 hours, which is 8 working days, it is important to compare the cost of the workers against the revenue. Even though this change in the number of workers increases the yards worker cost by 60%, in the long term the annual revenue of the yard increases by 40% (increase in the staff cost will be 7% of the new annual revenue).

This analysis in the yard aims to demonstrate an alternative perspective to the ship recycling operation through the modification of cutting lines and the potential benefits and losses over these changes. In the small operation presented here, 30% decrease in the operation time which leads to 40% increase in the annual revenue was achieved only with the improvements in the primary and secondary cutting zones. In addition to the decreased production time, this operation is also more energy efficient compared to the base scenario. This case study shows that with a slight change in the ship recycling method, around 50% less torch time (which leads to the reduced CO_2 emission for this operation) has been achieved.

7.14 Chapter Summary

This chapter has presented the improvement of the efficiency in the secondary dismantling zone of a selected ship recycling through the consideration of different cutting methods and discrete event simulation.

Chapter 8 Discussion, Future Recommendations and Conclusion

8.1 Chapter Overview

This chapter first highlights the novelties and the main contribution of this PhD study to the maritime knowledge and then presents the limitations of the study. Furthermore, future study ideas to overcome these shortcomings and to improve the framework are provided in this Chapter. Lastly, Chapter 8 summarises the overall conclusions of this PhD study.

8.2 Review of the Thesis and Its Novelty

Ship recycling industry is currently going through a transitional phase as a result of new international legislations and regulations. The profit-focused and sub norm ship recycling yards had damaged the reputation and the image of the industry. The illegal and sub norm operations conducted in these yards drew the attention of the public and policymakers which forced regulatory bodies to develop international regulations and standards. These regulations will change the way that ship recycling yards are designed and operated which will require the investments in order to be compliant with new regulations. Apart from the investments, the operating costs of the yards will increase due to the additional costs as a result of the HSE measures and safe operating procedures that can not be ignored by sub-norm yards. One way to compensate these investments is to optimise the current process and increase the efficiency; however, in the literature, there is a gap in the detailed approach to optimisation of ship recycling processes. This thesis aimed to address this gap through the application of discrete event simulation methodology and a novel framework to ship recycling yard design and operation stages. The simulation approach and the framework proposed in this thesis is the novel attempt to develop detailed ship recycling models to study the efficiency of ship recycling yards.

In Chapter 2 of this thesis, the current status of the ship recycling industry was introduced. First general overview of the industry, current market, ship recycling methods, and challenges and issues in the ship recycling industry were discussed in order to present an overall picture of the industry. Investigation of the literature demonstrated that there is a gap in the literature in the optimisation of ship recycling yard design and operations, hence, it was decided to address the productivity problems in ship recycling through a development of a simulation framework to design and optimise the ship recycling yards. Therefore, applicable simulation techniques, layout design methodologies were investigated. Moreover, studies about the simulation and layout development in ship recycling and similar industries, ship building and other dismantling industries were studied. Lessons learnt from these studies were summarised in this Chapter.

In Chapter 4, first the overall data collection and field study methodology followed in this thesis is presented. It was highly essential to conduct field studies and data collection campaigns to ensure the accuracy of the analysis conducted in this PhD study. Therefore, this PhD thesis collected significant amount of data through field studies, observations and expert consultations to be able to create simulation models as close as possible to the real-world examples. The amount of data collected from field studies and know-how transferred from experts can be considered as a major contribution to the literature as such data, which has never been available at research domain. Moreover, ship recycling methods around the world were investigated in detail in this Chapter. Respectively, beaching, slipway, quayside, dry-dock methods were investigated along with the processes that slightly differs from the country of application. Using the information collected, a generic ship recycling process flow was created which was used in this Chapter to develop the ship recycling simulation models and presented in this Chapter. The overall simulation framework, how to use the discrete event simulation, data needed for the simulation and using simulation to optimise the operation is discussed in this chapter. Chapter 4 also discussed the factors in ship recycling yard productivity that will be addressed through case studies.

Chapter 5 developed a novel discrete event simulation framework for ship recycling facility design and optimisation, which includes the design of ship recycling yard and optimisation of the operation of the yard. The developed framework can be applied to different ship recycling yard design and optimisation scenarios. The framework presented in this section is novel because it reflects actual ship recycling procedures currently implemented in ship recycling yards globally.

Chapter 6 presented the application of the developed framework and the approach for a ship recycling yard. First, an initial layout for the ship recycling yard was developed to meet the shipyard’s goals of annual scrap volume, number of staff, development plans for the future, constraints of the facility and so on. Bottlenecks in the current system were identified and various solutions are proposed and tested in the simulation environment to optimise the process. Different layout options, area capacities, different resource numbers and different techniques are modelled and tested for the shipyard as a case study.

Chapter 7 demonstrates additional case study and optimises the steel cutting process through the implementation of different cutting methodologies. This chapter first identified the cutting technologies suitable for the ship recycling industry and then compared the performance of these technologies using the discrete event simulation approach. The approach presented in this Chapter is unique as different cutting technologies were previously not compared on actual ship recycling processes.

8.3 Main Contribution of the Thesis

This thesis has focused on the development of a simulation framework for ship recycling industry to design and optimise the ship recycling yards. The study adopted a case-based approach where numerous design alternatives were studied through the proposed framework. The main aim of this study was to increase the productivity of ship recycling yards and optimise their recycling processes towards achieving cost-efficient facilities.

The overall research conducted in this PhD study is a significant contribution to the maritime literature as a novel discrete event simulation method, specific to the ship recycling industry to design ship recycling yards and to optimise the operations, was developed and validated. The main contributions of this thesis to the maritime literature is summarised below.

8.3.1 Process Flows and Models

Process flows developed in this study has not been developed in this detail level for different countries (to include data need for each step and resources involved) in the past. These process flows were essential to model the ship recycling process to represent the operation in the yard accurately.

Therefore, ship recycling process flows for all major ship recycling countries were investigated in a detailed manner through field visits, data collection studies and in study resulting in very rich material, practical operations and layout database. These process flows were then utilised to develop discrete event simulation models, which can be implemented to any ship recycling yard with minor modification in the model. Using these developed process flows and ship recycling simulation models, process optimisation and improvement techniques can be applied to any ship recycling yard to improve the overall productivity, profit and capacity.

8.3.2 Overall Framework

The developed "*Discrete Event Simulation Framework for Ship Recycling Facility Design and Optimisation*" is the first detailed ship recycling yard design and optimisation framework in the maritime literature. The framework is designed to provide the user flexibility and it can be used for different purposes; (primary and detailed) design and optimisation of a new yard or optimisation of an existing yard can be achieved by following the overall framework. The developed framework utilises the process flows and the process models developed in this thesis and provides scientific support to the stakeholder during the decision making stage. Design and investment cost-benefit analysis, operation modifications, resource optimisations and other operational decisions can be made using the framework. This type of support framework is novel for the ship recycling industry and can become a powerful tool with structured data collection.

8.3.3 Collected Data

Accuracy of the simulations and reliability of conclusions directly depends on the success of data collection and data process. Therefore, it was unavoidable to conduct field studies and data collection campaigns as part of this PhD study. Hence, significant amount of time was dedicated on field studies, data collection, observations and expert consultations to be able to create simulation models as realistic as possible with regards to the real world examples. The amount of data collected from field studies and know-how transferred from experts can be considered as a major contribution as such data was never available at research domain.

8.3.4 Technological Comparison

Technological alternatives for cutting operations were studied in this thesis and the impact on yard performance was investigated for the first time in the literature. Technologies were compared on a case base analysis and it was found that through the implementation of different technologies 60%

improvement in the process speed can be achieved. This is an important contribution to the knowledge, to both industry and academia, and the approach followed in the comparison of these technologies can be applied to different alternatives to further improve the performance. For example, it is possible to implement this framework for all different docking techniques; different surface preparation technologies, and material handling technologies.

8.3.5 Yard optimisation through the layout development

Ship Recycling yard design optimisation and ship recycling zone optimisation was conducted for the first time. Gaps in the literature with regards to the detailed yard design methods, were addressed in this thesis through a smart integration of simulation and layout design methodologies. Capabilities of the design method have been demonstrated through a case study and optimisation of the zones from micro-to-macro level. In the case studies, different zone sizes, alternative cutting technologies, different plate sizes, different resource (worker, cranes, and transporters) numbers have been considered.

8.3.6 Implementation of Arena Simulation Software to Ship Recycling

Developed simulation models was implemented to ship recycling yard through Arena simulation software, which was used in this area for the first time. Arena Simulation Software has being used in manufacturing, service and other industries for many years but this study utilised the software for the first time in the scope of ship recycling. Modelling approach through the Arena simulation software has been demonstrated in this PhD study and it is believed that this approach can be utilised and developed further by other researchers in ship recycling as well as discrete event simulation areas.

Arena simulation software has been applied to evaluate different options in the case studies; performance of different layout alternatives, resource combinations (worker, cranes, transporters, polygrabs etc.), technology solutions, alternative cutting technologies, different plate sizes, have been implemented through simulation approach.

To summarise, this PhD study also makes a significant contribution to current knowledge in the discipline through the developed process models, developed framework, collected data and the practical approach to compare different operational choices. The overall approach demonstrated in this PhD study will assist the industry to improve their operations.

8.4 Achievement of Research Objectives

The research objectives defined in Chapter 3 were achieved as shown in the following bullet points:

- The objective of “to investigate discrete event simulation method and to select most appropriate software package for this study” has been achieved as reported in Chapter 2. The available simulation software packages were reviewed as part of this thesis and Arena Discrete Event Simulation tool has been selected to model the ship recycling operations.
- Another aim was “to review and investigate typical ship recycling processes adopted in different countries where necessary conduct field studies in order to investigate process and material flow”. This objective was also achieved successfully. Field studies, literature review, and interview with stakeholders were conducted in order to develop the process flows for ship recycling approaches in different countries. Then these approaches were compared to generate a general ship recycling process flow. The development of the process flow was essential for the development of the simulation models and for the success of this PhD study.
- Building ship recycling yard procedures and process models in Arena simulation environment was an important task. The simulation knowledge and application to ship recycling processes was very limited, therefore, simulation approaches in shipbuilding and other

dismantling industries were carefully reviewed and the applicable modelling approaches in Simulation were implemented to ship recycling process models. To the best knowledge of the author, these simulation models were developed first time at this level of detailed in the literature to increase productivity of the ship recycling yards.

- Moreover, as targeted, the required data for the developed models were identified and a detailed data collection study was conducted to successfully complete the simulation. Due to the nature of the industry, data available for the researchers are very limited. On the other hand, data on the ship recycling yard procedures is essential for this study. Therefore, field studies, interviews and meetings with ship recycling stakeholders were organised to collect the data. This PhD study is the first attempt to collect the comprehensive data to model the ship recycling activities accurately.
- The principal objective of this study was “to develop a framework for the design and optimisation of ship recycling yards based on the simulation models”. This aim has also been achieved successfully. Current ship recycling processes and methods were investigated as part of Chapter 4 and using the information collected from this investigation, ship recycling simulation framework has been developed. Simulation approach has been combined with system engineering and Muther’s Systematic Layout Planning method to design and develop ship recycling yards and optimise the processes. The developed framework can be utilised to model and simulate ship recycling operations from macro (design and optimisation of yards) to micro level (optimisation of individual areas and specific operations) in a ship recycling yard.
- Another objective which was achieved is “to develop layout alternatives for the case study ship recycling yard and assess the performance of these layouts using discrete event simulation”. Simulation framework for yard design developed in this thesis was applied on a case study ship recycling yard. A ship recycling yard design to address the needs

of the owner and to meet the production goal was designed using the developed framework. The framework (presented in Chapter 5) is fully functioning and can be applied to design layout alternatives for ship recycling yard designs and assess these layouts to increase the competitiveness.

- Finally, to conduct case studies which focus on different process alternatives to improve the efficiency and profitability of the ship recycling yards. The case studies in Chapters 6 and 7 demonstrated that it is possible to increase the competitiveness levels of the ship recycling yards using a structured methodology.
- Through the case studies, this PhD study managed to increase the throughput of the yard from 30,000LDT per year to 70,000LDT per year by optimising layout, area, resources, and testing alternative technologies. Moreover, implementing plasma cutting increases scrap metal production speed in secondary zone by 60% which will lead to shorter dismantling times, hence, will lead to more ship dismantling capacity annually. Also, this thesis was able to identify the optimum number of workers to reach the dismantling goal of the yard in the short term (30,000 LDT) and in the long term (70,000 LDT).

8.5 Limitations of the Simulation Models and the Developed Framework

Modelling of the ship recycling processes is a complicated task considering the complexity of recycling processes that in some cases data could not be obtained; therefore, developed models include assumptions. Moreover, there were limitations and challenges experienced during the model building and development of the framework which are described in the bullet points below;

- Data can be collected more systematically which will improve the accuracy of the results and the reliability of the findings. For example, due to the practical reasons, it was not possible to collect data from all steps of the ship recycling processes. Especially data utilised in waste removal and storage procedures were estimated with expert consultations. This was due to the fact that the ship that was observed during the field study were already cleaned from hazardous wastes, therefore it was not possible to conduct time-motion study on this. In order to fill the missing data, interviews with ship recycling experts were organised. The accuracy of waste removal simulations could be improved with a proper time-motion study.

- The framework developed mainly focused on the improvement of the ship recycling operations and development of a ship recycling yard for increased production rates. However, the framework developed in this PhD study does not consider health, safety and environmental (HSE) aspects when assessing performance and optimising ship recycling procedures. However, it is known that improvements in HSE will indirectly affect the expenditure of the yards (e.g. by avoiding penalties and compensations). Current framework developed in this PhD study does not take such effects into account which can be considered as a limitation.
- Even though in real life each worker’s performance will be different subjected to their skill level and experience, in this study, it was assumed that workers have the same skill and production rate, the effect of training or experience was ignored in the simulations. More accurate simulation could be achieved by addressing this gap which will require comprehensive data collection from workers with different skill levels and experience.
- When modelling the placement of the blocks in the secondary dismantling zone, a grid-like arrangement was applied for simulation efficiency. In the real ship recycling yards the process is more spontaneous, cranes or trucks leaves the block on an empty space and worker dismantles the block as soon as he/she finishes the previous block. The approach followed in this PhD study has a limitation as the total area for secondary zone cutting was reduced due to the gaps between blocks.

- Material flow data was taken from the PhD study of Jain (2017). This data was captured from investigating the recycling procedure of a single ship. However, the type, age, size and other characteristics of the vessel will affect the amount and types of materials that can be found on board. As this PhD study utilises material flow data from one ship such ship specific differences are not taken into account which can be considered as a limitation.
- Detailed design framework was demonstrated in a case study which focussed on secondary zone of a ship recycling yard. However, each production zone may have its own characteristics and may require a different type of optimisation approach and associated performance criteria. Due to time constraints the detailed design framework was not applied for other zones and units in a ship recycling yard which can be considered as a limitation.
- When conducting the simulations in a case study it was presumed that a single shift work pattern is used in the ship recycling yard. Simulation models were developed to reflect this. However, it is known that some of the yards adopt multiple shifts to increase production capacity. Simulation models developed in this study do not take this into account which is a limitation that can be addressed in the future.
- Costs associated with investment, maintenance and disposal of the equipment are important cost steps, and therefore, these costs should be taken into account. In the future study, these costs should also be taken into account through detailed investigations on investment costs.
- This PhD presented a framework for the design and optimisation of layout and production processes in ship recycling yards. The optimisation was done via case-based investigations. Design alternatives were evaluated via pre-defined criteria such as cost or production speed. However, interrelations between different production units were not taken into account during optimisations. Therefore, this PhD conducts sub-system optimisation rather than full system optimisation which can be considered as limitation.

8.6 Recommendations for Future Research

Following are the recommendations, based on the limitations explained in Section 8.5, for the future researchers who would like to continue the research presented in this PhD study;

- The framework proposed in this PhD study can be improved by including the HSE aspects in the yard design. Hence, associated risks and potential risk control options can be systematically evaluated in a cost benefit framework. A future study can be conducted to improve the framework presented in this study by incorporating risks into alternative scenarios.
- This PhD study generated fundamental knowledge and data for ship recycling yard development and optimisation with discrete event simulation. Future studies can focus on systematic data collection from yards (process data, material flow analysis etc) which can increase the accuracy of simulations. Effects of ship size and type, worker quality etc can be studied to enhance the validity of optimisations.
- In this PhD study, significant amount of time was spent on developing the framework and generating the required data through field studies. Therefore, in terms of simulations for ship recycling yard improvements/developments, a case-based approach was adapted. Future studies can utilise the framework presented in this study and optimise each zone in a ship recycling yard (e.g. waste treatment, storages and workshop areas).
- Future studies can improve optimisation approach adopted in this thesis (i.e. sub-system optimisation) by implementing systematic optimisation methods to decide and choose design alternatives to create maximum overall performance.
- Circular economy is becoming more popular in EU. It is recognised that circular economy approaches (reuse, remanufacture, recondition, recycle) can be used to enhance value extraction from end of life ships. Ship recycling yards that re capable of reconditioning and

remanufacturing ship equipment may generate additional revenue. These approaches can be integrated into simulation models in a future study.

- The capital expense (CAPEX) and the operation expense (OPEX) of the new technologies should be taken into account. Also, full life cycle cost of these equipment should be considered in the future study to achieve more accurate result.

8.7 Conclusion

The research conducted in this PhD study focused on improving the performance and productivity of the ship recycling yards. In this research study, the development of a framework for design and optimisation of ship recycling facilities and operations was achieved. The developed framework and the simulation models are the first examples in the area of ship recycling. Aforementioned framework was applied on a two different case studies to design and optimise the ship recycling yards.

Overall concluding comments of the author of this thesis has been summarised in the below bullet points;

- In this thesis discrete event simulations were employed to improve ship recycling yards production efficiency. Work done in this thesis demonstrated that developed simulation framework is applicable to ship recycling yards and can be used for decision making by investors or other stakeholders.
- Calculations conducted in Arena DES software demonstrated that simulation is a very efficient tool to design yards and optimise the processes. Each case study modelled in this PhD study were run over one-year period and repeated 200 times (one year x 200 repetitions) in simulated environment. From this comprehensive data set average project completion durations were obtained. Creating such results in real life would require extensive amount of time and afford.

- Also, the simulation framework that is proposed in this thesis can be used from a what-if perspective to tests various design alternatives which can aid decision making in facility improvements.
- Data collection studies showed that in ship recycling sector there is a lack of data recording culture which prevented researchers to conduct more scientific studies to innovate and improve current practices. Therefore, the data generated in this thesis will provide foundation for future studies.
- The observations in the ship recycling yards show that ship recycling yards are planned and built by following previous tradition without taking advantage of modern calculations. Simulation results of this PhD study showed that by systematically studying the production efficiency, the throughput of the case study yard can be increased from 30,000LDT per year to 70,000LDT per year by optimising layout, area, resources, and testing alternative technologies.
- Results of the case study which focussed on evaluating alternative cutting technologies showed that implementing plasma cutting (vs oxy-LPG cutting) increases scrap metal production speed in secondary zone by 60% which will lead to shorter dismantling times, hence, will lead to more ship dismantling capacity annually. The method presented can be applied for different technologies to test the feasibility of using these technologies in ship recycling operations.
- Through the simulations conducted in this PhD study, capacity limitations of the specific zones were identified for the case study yard. It was identified that due to the area limitations and lifting and transporting capacity limitations, increasing the number of workers conducting torch cutting beyond 24 will not contribute to any improvements. Therefore, any further increase in worker numbers will impact on cost but will not provide the benefits expected by the yard owner.
- Upcoming regulations will enforce stricter HSE rules for ship recycling yards which will impact on the running costs, process times and in turn

overall productivity. Ship recycling yards need to recognise these challenges before they are encountered and develop alternative procedures to remain competitive. For example, effect of performing surface treatment before torch cutting operation was considered in a case study. Results show that before cutting with oxy-fuel in the case study yard, performing surface treatment on steel plates will increase the cost by 67%.

8.8 Chapter Summary

In this chapter, the originality of the research and its contribution to the current literature was presented. Limitations of the framework and the developed simulation models were also discussed, and suggestions were made for recommendation to overcome these limitations in the future studies along with future study ideas were shared with readers. Finally, this chapter concludes with the comments of the author about the PhD study.

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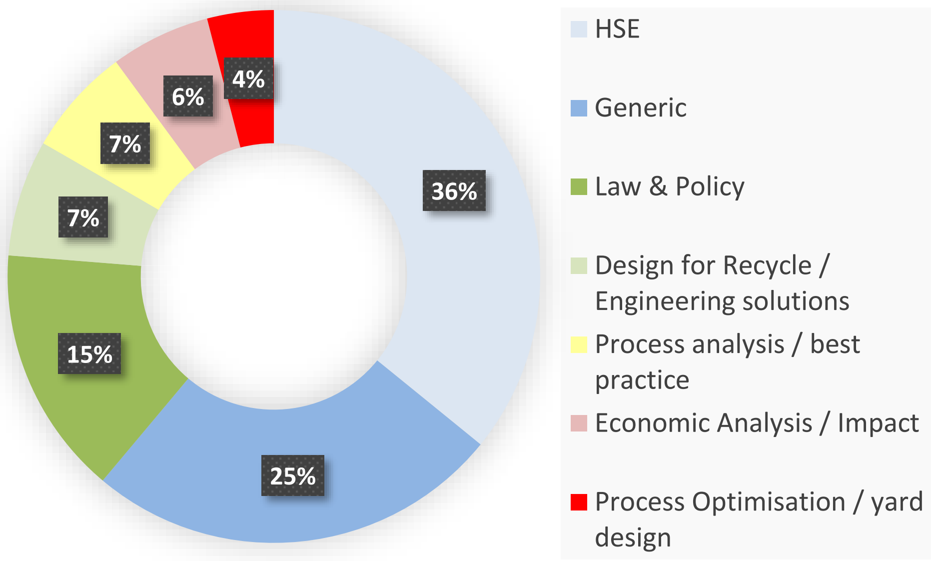
Appendix A: Literature Review Details



INDIVIDUAL RESEARCHERS

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Islam and Hossain, 1986)				●				-
(Zhijie, 1988)				●				-
(GREENPEACE, 1999a)	●	●	●	●				greenpeace, india, toxics, ship breaking
(GREENPEACE, 1999b)	●	●	●	●				greenpeace, india, toxics, ship breaking
(Andersen et al., 2000)		●	●	●	●			Ship decommissioning, Bangladesh, Chittagong, Recycling, Safety, Health, Environment (SHE)
(Andersen, 2001)		●	●		●			-
(Creese and Sibal, 2001)		●						-
(GREENPEACE, 2001a)	●	●	●	●				greenpeace, asbestos, toxics, ship breaking, asia
(GREENPEACE, 2001b)	●	●	●	●				greenpeace, asia, toxics, ship breaking
(Tewari et al., 2001)				●				heavy metals, microbial contamination, petroleum hydrocarbons, sewage, phytoplankton, zooplankton, ship scrapping industry
(Mattorano et al., 2001)			●					-
(Creese et al., 2002)		●						-
(FIDH, 2002)	●		●	●				
(GREENPEACE, 2002)	●	●	●	●				
(ILO, 2003)	●		●	●	●		●	metalworking industry, occupational safety and health, environmental degradation
(Reddy et al., 2003a)				●				Alang–Sosiya, Ship scrapping yard, Solid waste, Oiled sponge, Textile waste, Wood pieces

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Stuer-Lauridsen et al., 2003)	●	●	●	●	●			-
(Khan and Khan, 2003)			●	●				Trace metal, littoral sediment, ship breaking area, Bay of Bengal, Bangladesh
(Paul, 2004, Reddy et al., 2004a)				●				Alang–Sosiya, Mahuva, Intertidal sediments, Metal contamination, Bulk fraction, Fine fraction
(Reddy et al., 2004b)				●				Alang-Sosiya, DuLong's equation, Proximate and ultimate analysis, Ship scrapping, Waste to energy and energy potential
(Ahluwalia and Govindarajulu, 2005)		●					●	-
(Dimakopoulos, 2005)	●							-
(ECORYS, 2005)	●	●						-
(Mashreque, 2005)	●		●	●				-
(Reddy et al., 2005b)				●				Petroleum hydrocarbons, Heavy metal, Seasonal effects, Ship scrapping yard, Alang–Sosiya, Gulf of Cambay
(Reddy et al., 2005a)				●				Regression analysis, Solids, Marine vehicles, Oil insulation, Plastic insulation, Waste materials, Glass, Wool, Cotton, Rubber
(Adamides et al., 2006)						●	●	collaborative indirect process technology, lean and green management, ship dismantling
(Ahluwalia and Grover, 2006)	●		●	●	●		●	-
(Alkaner et al., 2006a)							●	-
(Alkaner et al., 2006b)						●		-

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Asolekar, 2006)				●				Ship dismantling, ship breaking, ship scrapping, India, Alang, solid wastes, hazardous wastes, recyclings
(Ayvatoglu, 2006)	●	●	●	●				-
(Bailey, 2006)	●		●	●	●		●	-
(Chaturvedi and Asolekar, 2006)				●				-
(Gramann, 2006)						●		-
(Hedlund-Astrom and Luttropp, 2006)					●			-
(Hossain and Islam, 2006)	●	●	●	●	●			-
(Karpowicz and Bruce, 2006)-							●	-
(Kinigalakis and Karling, 2006)							●	-
(Kostopoulos et al., 2006)					●			-
(Koumanakos et al., 2006)							●	-
(Mahindrakar and Asolekar, 2006)				●				-
(Mikelis, 2006)	●	●	●					-
(Reddy et al., 2006)				●				Alang-Sosiya, ship-breaking yard, small plastics, accumulation, intertidal sediments, microscopic fragmentation, FT-IR, SEM
(Stuer-Lauridsen and Ringgaard, 2006)	●							Ship recycling, Hazardous waste, Basel Convention
(Vedeler, 2006)						●		-
(Watkinson, 2006)	●							-
(Watkinson and Wingfield, 2006)	●							-

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Amin and Billah, 2007)				•				environmental degradation, environmental impact, environmental impact, assessment, environmental policy, intertidal environment, marine ecosystem, soil pollution, sustainable development
(Basha et al., 2007)				•				Alang-Sosiya, enrichment factor factor analysis Gopnath, suspended particulate matter
(Dilok, 2007)						•		-
(Dodds, 2007)	•	•	•	•				-
(Enger, 2007)	•							-
(Rousmaniere and Raj, 2007)			•	•				ship recycling, ship scrapping, shipbreaking, asbestos, Alang, Bangladesh, Mumbai, India, Basel Convention, Greenpeace; International Labor Organization, International Maritime Organization, International Metalworkers Federation
(Stuer-Lauridsen et al., 2007)	•	•	•	•				-
(Andersen, 2008)			•	•	•			-
(Charalambia Pylarinou et al., 2008)							•	-
(FIDH et al., 2008)	•		•					-
(Stuer-Lauridsen et al., 2008)	•		•					-
(Hossain et al., 2008)			•					ship scrapping, toxic chemicals, health hazards, accidents and casualties, medical, facility, low waged labourers.

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Kinigalakis and Lindvall, 2008)	•		•	•				-
(Knapp et al., 2008)		•						Recycling of ships, Ship scrapping, Ship demolition, Probability of scrapping, International convention on ship recycling, Econometric modelling, Binary logistic regression
(Lightburn and Townsend, 2008)		•			•			-
(Mahindrakar et al., 2008)				•				
(McKenna and Das, 2008)	•	•	•		•			-
(Melton, 2008)			•					-
(Mikelis, 2008)	•	•	•					Ship recycling; lightship; average age; standard deviation; recycling State
(Moen, 2008)	•							Shipbreaking, Basel Convention, Illegal traffic, Toxic ships
(Neşer et al., 2008)	•	•	•	•				Shipbreaking, Aliağa, Environment, Pollution, Hazardous wastes, Occupational health, Working safety, Basel Convention, Green recycling
(Neser and Unsalan, 2008)				•				-
(Sivaprasad et al., 2008)						•		-
(Sonak et al., 2008)	•							Basel Convention, Developing countries, Equity, Hazardous waste
(Sundelin, 2008)	•							
(Tilwankar et al., 2008b)				•				-
(Bhattacharjee, 2009)	•							Basel Convention, Ship Recycling
(Karim, 2009)	•		•					-

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Kumar, 2009)			•	•	•			-
(Milieu&COWI, 2009)	•	•						-
(NGO Ship Breaking Platform, 2009)	•	•	•	•	•			-
(Ormond, 2009)	•							-
(Pylarinou et al., 2009)							•	-
(Salim, 2009)			•	•				-
(Abdullah et al., 2010)			•	•				Beach breaking, ship recycling, environment monitoring; coastal pollution, remote sensing
(Chang et al., 2010)	•							Ship recycling, Marine environmental protection, International Maritime Organization
(Demaria, 2010)			•	•				Toxic waste management, Cost shifting, Material flows, Environmentalism of the poor, Environmental justice
(Deshpande et al., 2010)					•			
(Gregson et al., 2010)		•		•				Follow the thing, Waste, Value chains, Ships, Furniture, Consumption, Bangladesh
(Hossain and Rahman, 2010)				•				-
(Hossain et al., 2010)				•				Shipbreaking Yards, HPGe Detector, Radionuclides, Activity Concentrations, Dose Rates, Radium
(NGO Ship Breaking Platform, 2010)	•	•	•	•	•			-
(OSHA, 2010)			•	•	•			-
(Sarraf et al., 2010)		•	•	•				-
(Sivaprasad, 2010)					•			-
(Courtice et al., 2011)			•					Asbestos, Asbestos related disease, Bangladesh, Policy, Ship breaking

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Hossain, 2011)		•	•	•	•			-
(LR, 2011)	•	•	•	•		•		-
(NGO Ship Breaking Platform, 2011)	•	•	•	•	•			-
(Deshpande et al., 2012)			•					Ship dismantling, Ship breaking, Heavy metals, Worker exposure, Marine pollution, Air pollution
(Dhar et al., 2012)				•				Biodegradation, Fungi, Petroleum hydrocarbon
(Formount and Pavasovic, 2012)	•	•	•	•				-
(Khan et al., 2012)		•	•	•				Bangladesh, developing countries, environment, ship breaking, Sustainable design
(McKenna et al., 2012)						•		ship recycling, environmentally friendly ship, naval architechture, Naval architecture. Shipbuilding. Marine engineering, Automotive Engineering, Mechanical Engineering, Environmental Engineering
(Neşer et al., 2012b)				•				Ship recycling, Metal pollution, Sediments enrichment factor, Sediment quality guidelines, Aliağa Bay
(Neşer et al., 2012a)				•				Ship recycling, Polycyclic aromatic hydrocarbons, Aliphatic hydrocarbons, Sediment quality guidelines, Aliaga Bay
(NGO Ship Breaking Platform, 2012a)	•	•	•	•	•			-
(NGO Ship Breaking Platform, 2012b)	•	•	•	•	•			-
(Ormond, 2012)	•							-
(Pasha et al., 2012a)		•	•	•				Dismantle, EIA, SBRI, Sustainable

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(PROFUNDO, 2012)	•							-
(Shameem, 2012)	•	•	•	•	•			
(Shimizu et al., 2012b)					•			Afloat Method, Pilot Model, Ship Recycling, Water-Jet Cutting
(Siddiquee et al., 2012)				•				Trace metal affected area control site heavy metal alarming stage ship breaking area
(Sivaprasad et al., 2012)						•		-
(URANO, 2012a)	•				•			beaching, Japan, safe and environmentally sound, ship recycling, the Basel Convention, the Hong Kong Convention.
(Watkinson, 2012)	•							-
(Welaya et al., 2012)	•				•		•	Ship recycling, Ship scrapping, Marine environment protection, Ship breaking yard, Fuzzy logic approach
(Zakaria et al., 2012)		•	•	•				Ship recycling, ship dismantling, safety, safety hazards, environmental hazards
(Abdullah et al., 2013)				•				Beach breaking, Ship recycling, Coastal management, Environment monitoring, Pollution, Remote sensing
(O. Arslan et al., 2013)			•					Recycling, ship dismantling, training
(O. Arslan et al., 2013)			•					Ship dismantling, ShipDIGEST, safety
(Cameron-Dow, 2013)	•							Ship recycling, scrapping, Hong Kong Convention, Basel Convention

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Deshpande et al., 2013a)			•					Appropriate technology, heavy metals, occupational safety, policy, risk assessment, ship breaking, ship recycling, worker exposure
(Deshpande et al., 2013b)					•			-
(Hahladakis et al., 2013)				•				Recycling, Ship, WEEE, Heavy metals, Simulation reacto
(Hasan et al., 2013)				•				Trace metals, Pollution, Ship breaking, Sitakund Upazilla, Chittagong
(Hiremath et al., 2013a)			•					Health, safety and environment, occupational safety, fault-tree analysis, what-if-analysis, ship breaking, ship recycling, integrated risk assessment
(Hiremath et al., 2013b)					•			Ship recycling plan, oil tanker ship, IMO Guidelines, Inventory, Hazardous materials, Occupational safety, ship breaking
(Jain et al., 2013)	•							Hong Kong Convention, IMO, Ship breaking, Ship recycling
(Jan Willem van Gelder et al., 2013)	•	•						-
(Källmar et al., 2013)						•		Ecodesign, DFE, Ship industry, Ship recycling, ISO14006, POEMS, LEAP
(Kurt et al., 2013)			•					Accident investigation, occupational health and safety, ship dismantling
(Kusumaningdyah et al., 2013)		•						-
(LITEHAUZ, 2013)					•			

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(S. A. McKenna et al., 2013)			●					ShipDIGEST, ship dismantling, vocational education
(Mikelis, 2013b)	●	●	●					-
(Mikelis, 2013a)	●	●	●					-
(Mohammad, 2013)			●	●				
(Muhibbullah, 2013)			●					Ship breaking, Hazards, Vulnerability, Sitakunda, Bangladesh
(Neser et al., 2013)				●				-
(NGO Ship Breaking Platform, 2013a)	●	●	●	●	●			-
(NGO Ship Breaking Platform, 2013b)	●	●	●	●	●			-
(Pandey et al., 2013)	●							Green passport, Hong Kong Convention, Inventory of Hazardous Materials, health and Safety, International Maritime Organization, Hazardous Waste, Ship Recycling, Ship Recycling Facility Plan, Ship Recycling Plan
(Rai and Baumler, 2013)	●							Basel Convention, Hong Kong Convention, Ship recycling
(Sivaprasad and Nandakumar, 2013)						●		-
(Tunarli and Fet, 2013)	●							Ship recycling, Aliaga, stakeholders, Greenpeace, Turkey
(Vuori, 2013)	●		●	●				ship dismantling, ship recycling, environmental impact
(Watkinson, 2013)	●							-
(Aktaruzzaman et al., 2014)				●				Geo-accumulation index, Heavy metals, Pollution load index, Ship breaking yard, Transfer factor

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Alam and Faruque, 2014)	•							Ship breaking industry, Bangladesh, Basel Convention, Hazardous waste, Environmental pollution, Recycling of ships
(Hiremath et al., 2014)			•	•				Ecological Engineering, Eco-Industrial Networking, Industrial Ecology, Ship Recycling, Beaching method, Ship Dismantling, Health Safety and Environment, Hazardous Wastes Management
(Jain et al., 2014)						•		-
(Jobaid et al., 2014)	•	•		•				Ship Breaking, Existing laws, safety of workers, Environmental hazards, Child labor.
(NGO Ship Breaking Platform, 2014a)	•	•	•	•	•			-
(NGO Ship Breaking Platform, 2014b)	•	•	•	•	•			-
(Sahu, 2014)	•		•					-
(Taylan, 2014)	•	•	•	•	•			Ship recycling; Scrap metal; Hong-Kong Convention; Asbestos
(Thanikachalam, 2014)	•		•	•				Recycling, Environmental, Hazardous, Safety, Convention
(Wu et al., 2014)			•					Cancer incidence, Standardized incidence ratios (SIRs), Shipbreaking workers, Asbestos
(Yujuico, 2014)	•							Ship recycling, Hong Kong Convention. California effect, Demandeur pays
(Fakhruddin et al., 2015)				•				-

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Frey, 2015)	•	•	•	•				Ship Breaking; Hazardous Wastes; Environmental Injustice; Risk Globalization; World-Systems Theory; Ecological Unequal Exchange; Political Ecology; Capital Accumulation; Recycling
(Garmer et al., 2015)			•					Ship recycling, Ship breaking, Risk assessment, End-of-life vessels, Occupational risk
(Hiremath et al., 2015)				•				Ship recycling, Ship dismantling, Hazardous waste, Emission factor, Hong-Kong convention, European Legislation
(Hossain, 2015)		•	•	•				Ship recycling; Breaking; Dismantling; Socio-industrial safety; Environmental hazards
(Kara et al., 2015)				•				Trace elements, Sediment and seawater, Principal component analysis, Sediment quality guidelines, Industrial region, Air pollution
(Kurt et al., 2015)			•					risk, hazard, risk assessment, ship recycling, ship breaking, ship dismantling, job task analysis
(Mizanur Rahman and Mayer, 2015)		•						Bangladesh, Metal, Ship recycling, Social embeddedness
(NGO Ship Breaking Platform, 2015)	•	•	•	•	•			-
(Nøst et al., 2015)				•				-
(Sujauddin et al., 2015b)		•			•			Bangladesh Material flow analysis Ship breaking Lifespan
(Wu et al., 2015)			•					-

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Alcaidea et al., 2016)	•							
(Choi et al., 2016)					•			Ship recycling methods, Reefing, Cost–benefit analysis, Environmental impact, Life cycle analysis
(Haque, 2016)			•					-
(Hossain et al., 2016)	•		•	•				Ship breaking, Pollution, Environmental impact, Occupational health, Safety, Management system, Bangladesh
(ILPI, 2016)	•		•	•	•			-
(Jain et al., 2016)						•		End-of-life ships, Ship recycling, Material quantification, Ship scrap, Waste management, Design for recycling
(Koide et al., 2016)					•			ship breaking, ship recycling, hazardous materials management, material flow analysis, Bangladesh
(Mathesh and Babu, 2016)					•			ship dismantling, obsolete vessels, Ship Recycling, Beaching method, Energy Consumption
(Argüello Moncayo, 2016)	•							
(NGO Ship Breaking Platform, 2016)	•	•	•	•	•			-
(Rahman et al., 2016)		•	•	•				Ship recycling, Steel production, Life cycle assessment, Rerolling mills. Resource use, Greenhouse gas emissions
Rahman and Mayer (2016)	•	•						Administrative capacity , Compliance, Deposit refund system, Hong Kong Convention Policy gap analysis

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Watagawa et al., 2016)						●		-
(Ahammad and Sujauddin, 2017)	●	●		●				-
(Alcaide et al., 2017)	●							Ship recycling, Shipbreaking, European Union, Stakeholders' perceptions
(Devault et al., 2017)	●	●		●				Ship Recycling Facilities. Wrecks, Artificial reef, Ship recycling, Shipbreaking, Tourism, Diving, Working conditions
(Du et al., 2017)	●	●	●	●				
(Jain and Pruyn, 2017)	●	●						End-of-life ships, EU regulation, Hazardous waste, Hong Kong convention, Maritime economics, Material composition, Regulatory affairs, Scrap, Ship breaking, Ship recycling, Waste management
(Jain et al., 2017)						●		Ship recycling, Ship breaking, Green ship recycling, Material flow analysis, Waste management
(Jain, 2017)						●		
(Kurt et al., 2017)			●					Ship recycling, Ship dismantling, Noise exposure, Hearing loss, Occupational noise
(Kutub et al., 2017)		●	●	●				Ship breaking activities, Environmental impact, Health impact, Pollution, Safety of workers, Coastal management
(NGO Ship Breaking Platform, 2017)	●	●	●	●	●			-

Authors (year)	Law & Policy	Economic Analysis / Impact	Health & Safety	Environmental impact and waste management	Process analysis / best practice	Design for Recycle / Engineering solutions	Process Optimisation / yard design	Keywords / tags / indexing terms
(Rahman, 2017)		•		•	•			Ship Recycling, Beach Method, Economic Contribution, Environmental Impact
(Schøyen et al., 2017)	•	•		•				Ship-owner, Ship recycling, Ship scrapping, Environmental and safety conditions, Norway, Exploratory case study
(Sujauddin et al., 2017)					•			Bangladesh, industrial ecology intensity of use, material flow analysis (MFA), ship breaking industry, steel recycling

PROJECTS

	Law & Policy	Economic Impact	Impact on Health & Safety	Environmental impact and waste management	Process analysis and best practice	Training	Process Optimisation / yard design
ShipDISMANTL (2009)	•	•			•		
SAFEREC (2005)	•		•	•	•	•	
DIVEST (2008-2011)	•	•	•	•	•	•	•
ShipDIGEST (2013)	•		•		•	•	
Boatcycle Project (2012)	•	•	•	•	•		
BOATDIGEST (2013-2015)	•		•		•	•	
Shiprec (2013-2016)	•	•	•	•	•		
IMO (2017)	•	•	•	•	•	•	

Appendix B: Details of Discrete Event Simulation and Arena Simulation Software

B-1. Applicable Simulation Techniques and Tools

Simulation is the representation of operation, process or system in the real world over specific time, which allows predicting the steps and the problems on any stage (Banks, 1999b, Ljubenkov et al., 2008). Simulation is a powerful tool during the decision-making processes (Shannon, 1998, Banks and Gibson, 1997) to assess the alternative systems before changing an existing system or before building a new system. By employing simulation techniques, performance can be optimised or chances of failure can be reduced, unforeseen bottlenecks and under or over-utilization of resources can be prevented (Maria, 1997).

The history of (computer) simulation dates back to World War II era when Jon Von Neumann and Stanislaw Ulam used simulation to solve the behaviour of neutrons, and the success of the technique made the simulation a popular tool within the scientific community and industry (Cooper et al., 1989, Shinde, 2000). The first simulation codes date back to late 1950's and, through the years several different but the first versions of the well-known simulation codes like SIMSCRIPT or SIMULA were developed in 1960's (Reitman, Shinde, 2000). Throughout the years, different modelling systems such as SIMAN or EXTEND were developed, and these systems are being used in many different areas and industries to solve complex problems and identify solutions.

Today, simulation has a wide range of use in different industries with numerous application areas (Mousavi, 2011). Application area of the simulation is very wide, which includes but not limited to manufacturing industry, service sectors and transportation sectors to supply chain applications. Organisations, small and medium enterprises, large companies, public sector use simulation tools to answer the question on the performance and what if situations for systems such as; what is the best layout for the factory, what are the resource requirements, and if the production capacity to be increased and how much. If there is a renewal for a business plan, simulation can give reliable answers to the possible options for real or conceptual systems. Furthermore, simulation requires less investment and less time compared to experimenting on the real system, and it is widely used in different industries to reduce time and cost of the process. Furthermore, problems encountered in the systems can be modelled with simulation methods. The overall benefits simulation can be listed as

- Simulation can be used to investigate the complex systems and the subsystems
- It can be used to assess the effect(s) of organisational, environmental or functional changes on the system, process or the output of the system,
- Simulation can be used to verify the analytical solutions
- Simulation can be used to support decision making on new policies, decisions or investment

B-1.1. Definitions

In order to simulate a process or an operation, first the study "**system**" should be generated or "**modelled**" in an artificial environment (i.e. in the computer), and the observation of this artificial system can answer)

The term **"system"** is defined by Schmidt and Taylor as a collection of **entities** (e.g., people, cars, workers or machines) that act and interact together toward the accomplishment of some logical end (Schmidt and Taylor, 1970). Systems include three elements; input, process and output (Figure B.1).

Figure B.1: Input-Process-Output Model (Mousavi, 2011)

Model, on the other hand, is the simple representation of a system which is under consideration/review (Maria, 1997) and includes relationships to describe the **state** of the system. The model helps to predict the effect of different variables to the system. Therefore it should be close as much as similar with the working system, but also it should be easy to comprehend and experiment.

State of the system is the set of data that captures information and variables to describe the system (Altiok and Melamed, 2010).

Entities are the dynamic objects of interest (machine, customer, ship, car, and so forth) that undergo processes and move along the system (Kelton, 2002, Banks, 2005). In the scope of ship recycling entity can be end of life ship, blocks dismantled from the ship, and any other material/equipment (or even waste) that was removed from the ship depending on the model scale.

B-1.2. When to use simulation

Simulation has become one of the most commonly used and accepted tools in analysis and research due to the development of the simulation languages, software and increasing computing capabilities (with a lower cost per operation) (Banks, 2005).

The appropriate circumstances to use the simulation were discussed by different researchers (Naylor et al., 1966, Shannon, 1998, Banks, 2005) and simulation should be applied;

- If there is no analytical solution to the problem or complete mathematical formulation or if the mathematical procedures are very complex (and if the simulation is more straightforward solution),
- If the system is a complex system or consists of complex subsystems that is hard to solve through analytical methods
- The actual experiment difficult due to the limiting conditions
- Time compression or different time frame is required

Also, the simulation should not be used when,

- there is a solution to the problem through common sense or analytically,
- experimenting on the system is easier than simulation,
- cost of simulation exceeds the saving through the simulation,
- necessary resource(s) (e.g. money) and time is not available,
- there is no reliable data,
- expectations from the simulation are overly ambitious or not clear,
- system is too complicated.

B-1.3. Benefits and Shortcomings of the Simulation Approach

As mentioned before, simulation is a very powerful tool to analyse the behaviour of the systems and commonly used by decision-makers due to its advantages over the analytical or mathematical models. The benefits of the simulation were discussed by many researchers (Banks, 1999a, Banks, 2005, Law and Kelton, 1991, Pegden et al., 1995, Schmidt and Taylor, 1970).

Advantages of the simulation are;

- Simulation is a very flexible tool; it can be applied to any case or any situation
- The basic concept of simulation is easy to understand and master, therefore, during the reporting to the management/customer/end-user, it is easier to explain the findings (Shannon, 1998).
- Using simulation, cases that are too complicated or large to solve mathematically can be analysed. Also, simulation can study the specific relations that would create a problem with analytical or numerical modelling.
- Simulation can be used to answer a wide range of questions; resource utilisation, waiting times, or fault percentages of a model (Van der Aalst et al., 2010). Bottlenecks and problem areas of the system can be identified with the cause of these bottlenecks/problems in any system. Also, the cause of a particular event or phenomena can be found using the simulation approach (Pegden et al., 1995). Moreover, different solutions can be tried using simulation

- New/alternative resources, layouts, designs, technologies, and so forth can be tested using the simulation before investing. Therefore, the what-if questions can be answered with only simulation costs.
- Interaction of different variables can be tested, and the effect of different variables to the system can be tested (Pegden et al., 1995).
- It can be used to support the decision making for the staffing policies, operating procedures, decision rules, organisational structures without disrupting current operations (Shannon, 1998)
- Time can be flexible in the simulation, it can speed up (to study a behaviour easily over a long period of time), speed down (to study behaviour more closely), expanded (to see long term behaviour), compressed (to understand short term behaviour) or a certain period can be looked at.

Apart from these benefits, simulation also has its shortcomings;

- Simulation is not always easy, and it can be time-consuming to prepare and run the model (and sometimes costly).
- Interpretation of the simulation results can be difficult.
- Model building requires training and experience as well as creativity in some cases.
- The simulation may not always produce the correct results, events that occur in a simulation model may occur in reality, but the reverse of this is not always true. Events that may happen in reality that might not have been covered by the simulation model (Van der Aalst et al., 2010).
- Assumptions made during the modelling steps need to be clearly stated.

B-1.4. Different Types of Simulation Models

Simulation models can be classified as iconic and symbolic (Mousavi, 2011). Iconic models have a physical resemblance to the real system (e.g. globe), and symbolic models are the abstractions that represent the behaviour of the system (Perry, 2001). Symbolic model types are;

- Deterministic vs stochastic
- Static vs dynamic
- Continuous vs discrete

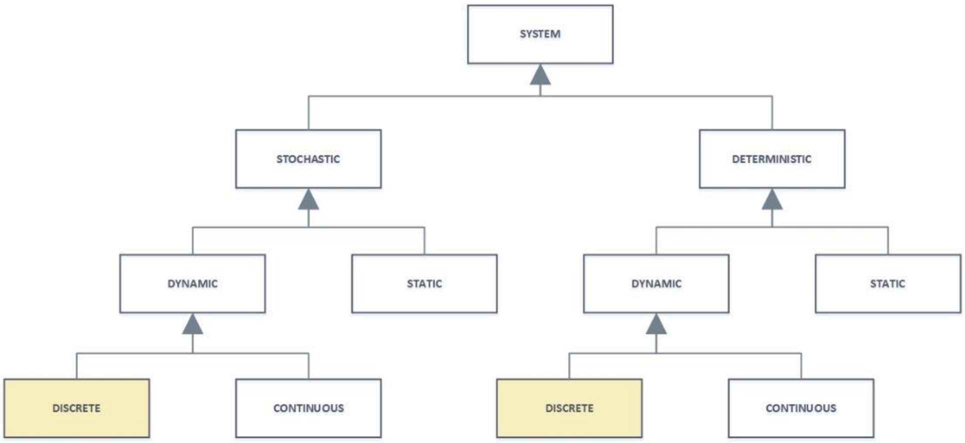


Figure B.2.: General types of system and modelling (Rossetti, 2015)

B-1.4.1. Deterministic vs Stochastic Models

Deterministic models are used when the result can be established from a series of conditions (Kelton, 2002). In the deterministic model, there are no random or uncertain components, for example, if a doctor's clinic is working with a strict appointment service and fixed times it would be regarded deterministic.

On the other hand in the stochastic modelling, elements might change randomly, stochastically, for example, accident & emergency service of the hospital, the simulation would be stochastic. Deterministic model assumes that its outcome is certain if the input to the model is fixed, regardless of the replication number the result will be same (Mousavi, 2011). However, the stochastic model will provide different results due to the random elements in the model. Therefore, it can be argued that the stochastic model is much more informative as it provides more information on the behaviour of the system in different inputs and uncertainties (Van der Aalst et al., 2010).

B-1.4.2. Static vs Dynamic Models

If the system does not change significantly concerning time, it means the system is static, if the system changes with time, then the model called dynamic (Rossetti, 2015). In other words, in the static simulation, time does not play a role but in the dynamic simulation, the time has an important role (Law and Kelton, 1991).

B-1.4.3. Continuous vs Discrete Models

The state of the system can changes continuously over time; when an aeroplane is flying, the velocity diagram changes according to the speed, position, angle, or in a reservoir, water level changes all the time through precipitation and evaporation (Kelton, 2002). On the other hand, in the discrete event case, changes can only occur on defined points; e.g., worker numbers increases by the shift start or number of machinery is the same. It is also possible to mix both types of simulations in a system and have a combined simulation.

B-1.5. Discrete Event Simulation (DES)

The DES is the term used to describe a simulation of a system and DES concerns the modelling of a system as it evolves by representation in which the state variables change at separate points in time (Law and Kelton, 1991). DES models are suitable for the systems that change at discrete points (Banks, 2005) whose elements can be modelled as interacting with one another only at discrete points at a time. Therefore, ship recycling is perfectly suitable for discrete event simulation as the change also occurs at discrete points in time when the ship recycling process is considered (e.g. blocks cut in the primary zone or when they are transferred to secondary zone, equipment removed after docking). DES used to analyse the systems, evaluate strategic decisions, and test tactical solutions, however, in order to understand and analyse a system a number of terms need to be defined (Banks, 2005). Table demonstrates the components of a system.

Table B.1: Components of the discrete event simulation (Altiok and Melamed, 2010, Banks, 2005)

System State	In the DES, the model has a state at any point at a time, the system state is the value of variables of the system that collects information and allows us to describe the system and changes over time.
Event	The event is an incident/occurrence that changes the state of the system
Entity	The entity is the object or component of interest in the system
Attributes	Attributes are the properties of entities
Variables	A Variable is the information piece that represents the characteristics of the system
Resources	The resource is the provider of the service to entities in the simulation system
Queue (List/set)	Collection of entities ordered/waiting in the given logic
Activity	Duration of time of specified length
Delay	Duration of time of unspecified indefinite length
Clock	The changes in the simulation model are governed by the clock, which is a variable to represent the time

It should be noted that terminology given in Table can change according to the software. In the next section, Discrete event simulation tools will be investigated and a simulation tool for ship recycling will be used.

B-1.6. Selection of a simulation tool for ship recycling industry

Discrete event simulation can conceptually be done by hand calculations, but the amount of data that must be stored and manipulated makes the use of computer essential for most real-world systems (Rossetti, 2015). Usually, a software tool (which can be directly used or software packages that utilises the simulation languages) are used for the construction of a simulation model in the computer environment (Van der Aalst et al., 2010). These tools ensure that the computer can simulate the condition projected by the model.

Currently, there are more than 100 commercial languages available for discrete event simulation operations (Rossetti, 2015, Alexopoulos and Goldsman, 2017). Some of these languages are general-purpose programming languages such as FORTRAN, SIMSCRIPT, Visual Basic, C/C++, Java (Altiok and Melamed, 2010), but these tools require expert knowledge on programming, and also they do not provide simulation objects or options like the simulation-oriented specific languages. Because of the power and capacity of the computers, specialised simulation languages, such as SIMAN, PROMODEL, GPSS, SLAM, MODSIM, were developed throughout the years (Pritsker, 1986, Belanger, 1990, Schriber, 1991, Benson, 1997, Altiok and Melamed, 2010, Rossetti, 2015).

Working with simulation languages have the following advantages; reduced programming time, models are easier to understand with flowcharts, models are easier to change in software and error detection is also more comfortable with simulation software (Shinde, n.d., Law and Kelton, 1991)

The choice of a simulation language is difficult as there are many different options available commercially, and each has their advantages and disadvantages.

Even though the operation can be simulated using any one of the software available in the market, it is crucial to select the correct software for the purpose as well as for the operation (Balachandran, n.d.). Available software for discrete event simulation is summarised below (Balachandran, n.d., Dias et al., 2016, McGinley, 2017). Detailed information about the use areas can be found in McGinley's survey (McGinley, 2017).

Table B.2.2: List of available simulation software, compiled from (Balachandran, n.d., Dias et al., 2016, McGinley, 2017).

20-Sim	AnyLogic	Arena	AutoMod
Awesim	EASY5	Enterprise Dynamics	ExtendSim
FlexSim	GPSS World	Idef	Intrax

Manufacturing Engineering	MATLAB	Micro Saint	Modsim
Plant Simulation	ProcessModel	ProModel	Prosolvia
QUEST (Delmia)	ShowFlow	Simba	SimCAD Pro
SimEvents	Simio	Simplorer	SIMPROCESS
Simul8	SLX + Proof 3D	VisualSim	WITNESS

As mentioned above, selecting a language or simulation tool is a difficult choice involving many different criteria such as cost, ease of learning, flexibility, support, programming costs, run-time costs, animation capabilities and additional features. The most critical criteria amongst these are summarised below (Law and Kelton, 1991, Kleijnen and van Groenendaal, 1992, Shinde, n.d.);

- Most essential feature to look for in a simulation package is the modelling flexibility. Simulation package should be flexible to allow different modelling approaches because all systems are different.
- Model development should be easy. Considering the nature of the ship recycling industry, projects sometimes might have short time frames. Therefore the model development in the software should be fast and easy.
- Also, simulation software should be fast. Sometimes, the simulation should be run multiple times to debug, validate or to get accurate results. If the simulation software takes too long to execute, it is not ideal.
- Even though the ease of use is essential, accuracy, capacity to investigate detail, ease of learning are also important.
- Customer support is also essential. Sometimes it might not be possible to identify the problem and debug the model and support from the programmers might be needed. Software companies with excellent customer support can help technically to the user.
- Simulation software should support (import/export) third party software such as Microsoft Office, Autocad and so forth. Compatibility with

external software provides modeller with the flexibility both during modelling and analysing the outputs of the simulation.

Following the investigation of available simulation software listed in Table 2.2. using the criteria listed above Arena discrete event simulation software was selected as the simulation environment to use in the ship recycling framework. Reasons for selecting Arena simulation software are;

- Arena has a simple user interface and does not require programming skills for the majority of simulation models. All the properties of simulation elements are pre-programmed in the software, therefore using existing modules it is possible to efficiently model systems.
- Arena can import from third-party software such as Microsoft Excel and Visio and CAD software such as AutoCAD. Import is a critical feature for data input for the simulation distributions and as well as input for drawings and plans (in case of layout planning).
- Arena facilitates customised reports at the end of simulation runs which makes analysis easier sometimes considering outputs of a simulation can be complicated
- Built-in applications of Arena such as “Input Analyzer”, “Output Analyzer” and “Process Analyzer” are beneficial to the user to generate distributions, analyse outputs or processes with changing parameters. Input Analyzer also helps the user to generate random distributions, which is quite useful when a data is not available.
- Animation helps to identify the problems and errors with the simulation model (Shinde, n.d.). Animation capability of Arena simulation software is very high and animating the simulation models is very easy and straightforward process in Arena.

B-1.7. Steps of the simulation

Model building for simulation is a continuous learning process that proceeds gradually in a stingy way, and simulation model should be developed step by step, starting from the simple properties of the system and moving gradually to the complete system (Pidd, 1998). Figure B.3. shows the overall steps of a simulation study, and the relationship between these steps (Law and Kelton, 1991, Shannon, 1977, Shannon, 1998, Kelton, 2002, Banks, 2005, Gordon, 1978). These steps given in the figure are not a rule to follow but guidance; some studies may follow different steps. Moreover, a simulation study is not always sequential (Law and Kelton, 1991); in some studies some steps may need to be repeated during the modelling (for example, author of this thesis went back to the previous steps as the understanding of the recycling industry increased during the preparation of the framework of this thesis).

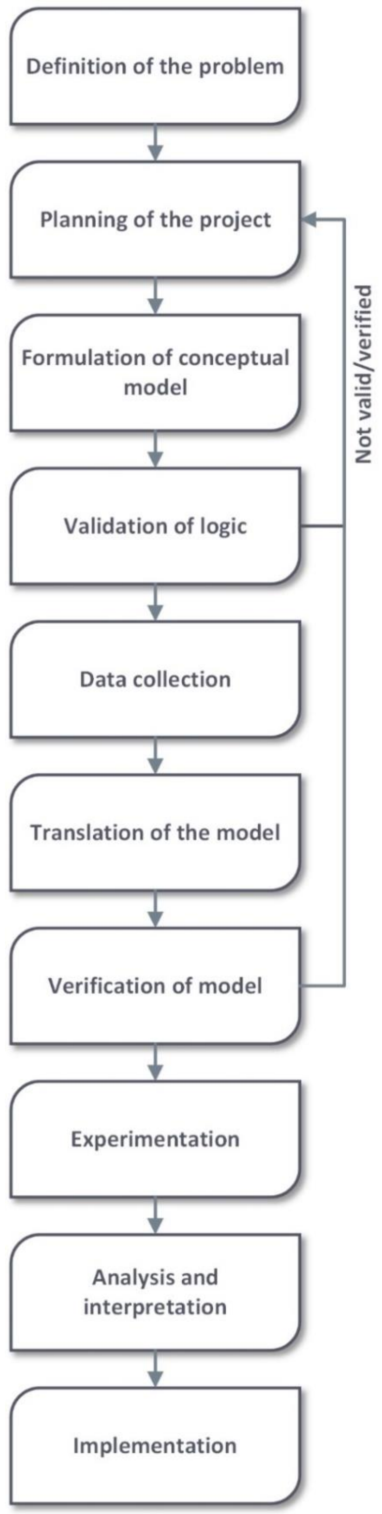


Figure B.3: Steps in the simulation (Modified from: Law and Kelton (1991), Shannon (1998), (Banks, 2005)

1. **Definition of the problem:** Simulation study should start with the **definition of the problem** (Law and Kelton, 1991). In this step, the system should be investigated (if the decision makers do not provide the definition) and symptoms of the system should be diagnosed (Banks, 2005). Following this, the problem(s) of the system can be defined. Also, the goals and objectives of the study should be set at this step.
2. **Planning of the project** As a next step, the **overall planning of the project** can be done to ensure that the resources and time are sufficient to conduct the simulation project.
3. **Formulation of conceptual model:** Following the planning stage, the system should be investigated in detail to **formulate** the flow and **create the conceptual model of the system**. The entities, all stations/workshops, subsystems, flow patterns and resources (with alternative designs) should be collected to develop flowcharts to show the logic of the system (Shannon, 1998). The construction of this concept model requires creativity. Hence, it is an art as much as science (Banks, 2005).

4. Validation of logic: At this step of the study, it is essential to conduct a **validation of the conceptual model**. It can be done by involving people in the simulation study who are familiar with the operations and processes of the system (Law and Kelton, 1991).

5. Data Collection: If the logic of the concept model is valid, a comprehensive **data collection** should be conducted. In this stage, required operation/process data for the model should be systematically collected from the system. The "garbage in – garbage out" cliché applies to simulation modelling, and the quality of the data collection will influence all the output of the simulation (Shannon, 1998). Data collection is one of the most time-consuming step of the simulation. In addition to the observation data, the following can also be used as a data source (Shannon, 1998);

- Historical records,
- Similar systems to investigated system,
- Operator estimates,
- Information from the vendor, designer estimates and data sheets,
- Theoretical considerations,
- Data and results of previous studies.

6. Translation of the model: Once the data collection is finished, the **model can be translated** to the simulation language through the software of choice.

7. Verification of model: After the translation of the model, test runs should be done with the simulation model in order to **verify the model**, sensitivity of outputs and the data used. If there is a similar system, output from pilot runs can be compared with existing performance data (Law and Kelton, 1991).

8. Experimentation: If the outputs of the test runs are not satisfactory, previous steps should be revisited and reviewed, but if the outputs are satisfactory, the **experiment step** of the simulation can start. At this step, runs of the existing and alternatives should be done to find the optimum performance (productivity, cost, time) of the system. Length of the simulation, boundary conditions and a number of replication for each alternative should be considered at this point.

9. **Analysis and Interpretation:** The output data from these runs should be **analysed, interpreted**, documented and presented to the decision makers. For the analysis usually, statistical techniques are used.

10. **Implementation:** If the result of the analysis is satisfactory and decision-makers are also happy with the outcome, **implementation** of the best alternative can start.

B-1.8. Statistical Distributions

As real-world situations cannot be predicted entirely (Banks, 2005) some statistical models are required to model some real-world situations. A suitable model can be generated by observing the simulation system that is under investigation. Then, a distribution model should be selected by the modeller, and selected distribution model should be tested for fitness to data.

This section will first briefly summarise of the theory and distributions. Distributions that are not covered in this section can be further investigated through other references (Law and Kelton (1991), Kelton (2002), Banks, (2005), Altiok and Melamed (2010) to name a few).

As mentioned in section 0, there are two different event types, deterministic and probabilistic. Deterministic events are the events that will occur with certainty (sun-rise and sun-dawn) while probabilistic events are that occur randomly (Mousavi, 2011).

B-1.9. Probability

In a simple term, Probability is a measure of the occurrence rate of a random event (Altiok and Melamed, 2010). Probability is denoted by P(E) and measured on a scale between 0 and 1 for the event “E” in the sample space S (Ash, 2008). Sample space is the complete set of all possible outcomes of random experiment and event is the subset of this sample space (Kelton, 2002). The properties of the probability;

In sample space S,

$P(S) = 1$

$P(E) \geq 0$

$\varnothing$ is an empty event,

$P(\varnothing) = 0$

$P(E') = 1 - P(E)$ where "E'" is the possible outcomes other than "E"

If E, F, G are events and exclusive then $E \cap F \cap G = \emptyset$, then,

$P(E \cup F \cup G) = P(E) + P(F) + P(G)$

If $E \subset F$, then $P(E \leq P\ (F)$

Conditional probability plays a significant role in the probability theory (Altiok and Melamed, 2010) and as the name also implies, the probability of the occurrence of an event is dependent on the occurrence of another event. It can be expressed as (Mousavi, 2011);

Assuming that E and F are events $(P(F) \neq 0)$ and

$$P(E/F) = \frac{P(E\ \cap\ F)}{P(F)}$$

B-1.10 Random Variables

According to Van der Aalst et al. (2010) simulation experiment is more than replaying a modelled situation as assumptions on the system together with its environment are needed to replay an event in a computer. The behaviour of the environment is determined by randomisation (Van der Aalst et al., 2010). The environment and the system can be defined in many different ways and can be very complex; one way of simplification is defining a random variable relating to them (Kelton, 2002). Random variables can be described "as the values of outcomes observed during an experiment" (Mousavi, 2011). The probabilistic properties of random variables are characterised by their distribution functions, also abbreviated as distributions (Altiok and Melamed, 2010). During the simulation, the computer takes random samples from the distribution function introduced by the user. These random (samples) numbers are generally produced via a random number generator procedure (Altiok and Melamed, 2010).

Even though the term “random numbers” used commonly, the numbers generated through the random number generator procedure is not truly random. The computer is a deterministic system and random number generator is a deterministic procedure. Therefore, the generated number stream can always be recreated (Kelton, 2002, Altiok and Melamed, 2010, Van der Aalst et al., 2010) which allows the recreation of the simulation. This is important as the simulation result may needs further examination.

B-1.11. Probability Distributions

In discrete event simulation, distribution functions are used to match the input (data collected) with the known functions and using the goodness-of-fit techniques the best fit to the data is selected (Mousavi, 2011). The random number generator is used to obtain samples from the various probability distributions. These distributions are built-in functions in most of the simulation tools and help the user to generate random numbers through probability distributions (Kelton, 2002). In this section, the most common probability functions are explained further next.

B-1.11.1. Beta Distribution

The beta distribution is a two-parameter distribution over a finite interval [0, 1]. It is used for random variables that have clear upper and lower boundaries. As it can take on a wide variety of shapes, Beta distribution (Figure B.4) can be used in the cases with absence of data to form a rough model. The beta distribution is denoted as BETA (β, α).

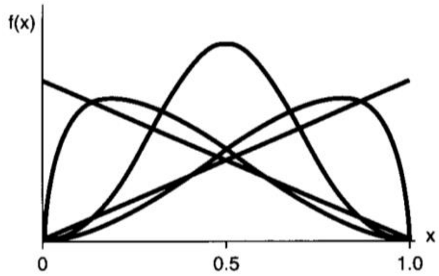


Figure B.4: Probability Density Function (Kelton, 2002)

The function expression of the Beta distribution;

$$f(x) = \frac{x^{\beta-1}(1-x)^{\alpha-1}}{B(\beta,\alpha)}$$

$$where\ B\ is\ given\ by\ B(\beta,\alpha) = \int_0^1 t^{\beta-1}(1-t)^{\alpha-1}dt$$

As mentioned, the distribution ranges from 0 to 1 and sample X can be transformed to scaled beta Sample to a to b range through $Y = a + (b-a)X$ (Kelton, 2002).

B-1.11.2. Discrete

Discrete distribution is defined by the set of n possible discrete values that can be returned by the function and cumulative probabilities associated with these values (Figure B.5). Cumulative probabilities (c) for the values (x) is defined as the probability of obtaining a value that is less or equal to the value. Cj is equal to the sum of p(x_k) for k going from 1 to j (Altiok and Melamed, 2010).

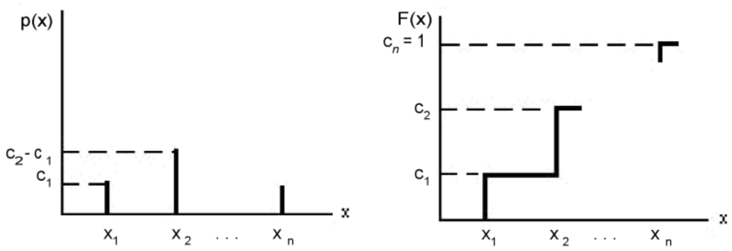


Figure B.5: Discrete Distribution (Left: Probability mass function, Right: Cumulative distribution function) (Rockwell Automation, 2010)

The discrete empirical distribution is frequently used to incorporate discrete empirical data directly into the model and in assignments such as the job type, or the size of the batch for an arriving entity (Kelton, 2002).

B-1.11.3. Exponential

Exponential distribution (Figure B.6) is often used to model random arrival and breakdown processes, and it is generally inappropriate for modelling process delay times. The exponential distribution is denoted by Expo(β).

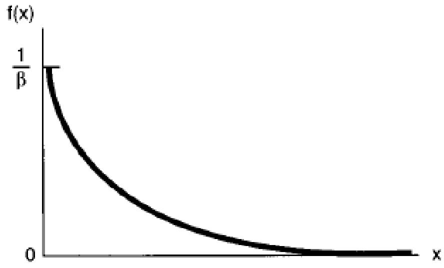


Figure B.6: Probability density function (Kelton, 2002)

$$f(x) = \frac{1}{\beta} e^{-x/\beta}$$

The exponential distribution is often used to model arrivals and breakdown processes. However, exponential distribution is generally considered as inappropriate to model the delay times of the process.

B-1.11.4. Continuous

The continuous function returns a sample which is a real number between x_1 and x_n from the user-defined distribution. Pairs of cumulative probabilities ($CumP_1$) and associated values (Val_1) are specified (Figure B.7). Cumulative distribution function F(x) is given as (Kelton, 2002).

$$f(x) = \begin{cases} c_1 & \text{if } x=x_1 \\ c_j - c_{j-1} & \text{if } x_{j-1} \le x < x_j \text{ for } j = 2, 3, \dots n \\ 0 & \text{if } x < x_1 \text{ or } x \ge x_n \end{cases}$$

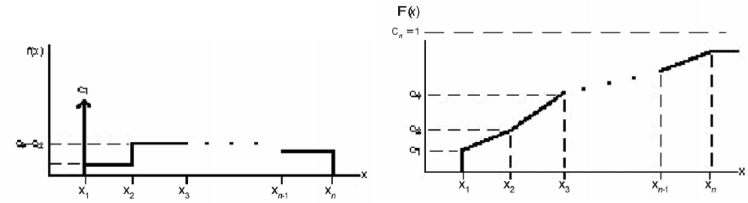


Figure B.7.: Continuous distribution (Left: Probability density function, Right: Cumulative distribution function) (Rockwell Automation, 2010).

The continuous distribution in Arena can be used to incorporate actual data for continuous random variables directly into the model. This distribution can be used as an alternative to a theoretical distribution that has been fitted to the data, such as in data that have a multimodal profile or where there are significant outliers. Continuous function in Arena denoted as CONT(C_1, x_1).

B-1.11.5. Normal

Normal distribution, which is denoted by NORM (μ, σ^2), is known with the familiar bell shape (Altiok and Melamed, 2010).

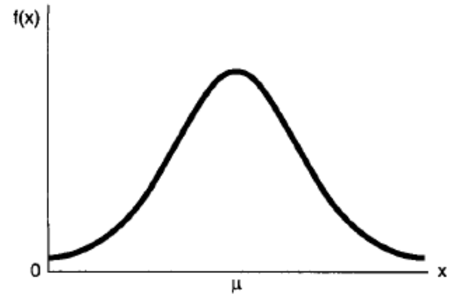


Figure B.8: Normal Probability Density Function

The function of x

$$f(x) = \frac{1}{\sigma x\sqrt{2\pi}} e^{\frac{(x-\mu)^2}{2\sigma^2}}$$

A normal random variable is used to model many random phenomena that can be expressed as sums of random variables. It is also used empirically for many processes that appear to have a symmetric distribution.

B-1.11.6. Poisson

The Poisson distribution (Figure B.9) is a discrete distribution that is often used to model the number of random events occurring in a fixed interval of time. The Poisson distribution is also used to model random batch sizes.

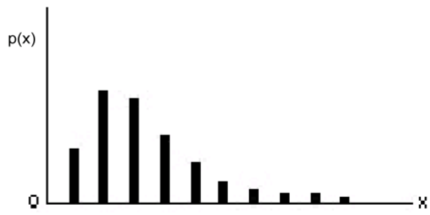


Figure B.9: Poisson Probability mass function

$$f(x) = \frac{e^{-\lambda}\lambda^{x}}{x!}$$

B-1.11.7. Triangular

The triangular distribution (Figure B.10) is used in when estimates (or guesses) for the minimum, maximum, and most likely values for the system are available but the exact form of the distribution is not known..

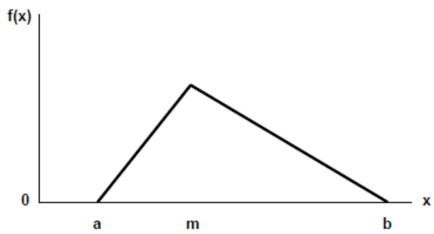


Figure B.10: Triangular probability density function

Probability function of a variable x is,

$$f(x) = \begin{cases} \frac{2(x-a)}{(m-a)(b-a)} & \text{for } a \leq x \leq m \\ \frac{2(x-a)}{(b-m)(b-a)} & \text{for } m \leq x \leq b \\ 0 & \text{in other cases} \end{cases}$$

B-1.11.8. Uniform

The uniform distribution (Figure B.11), which is denoted by UNIF (min, max), is the simplest continuous distribution (Altiok and Melamed, 2010).

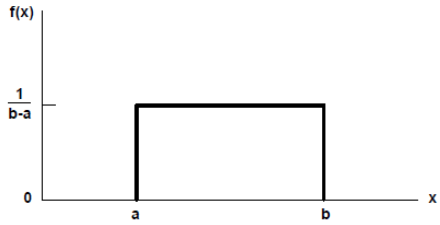


Figure B.11: Uniform probability density function

The probability density function of X;

$$f(x) = \frac{1}{b-a}$$

The uniform distribution is used when no (or limited) information other than the range is available as the function considers all values over the range are equally likely.

Distributions (including the ones that were not described above) and the modelling situations for these distributions are summarised in Table B.3

Table B.3: Distributions and the modelling situations (Altiok and Melamed, 2010)

Distribution	Modelling situations
Beta	Useful for modelling task times on bounded range with little data, modelling probability as a random variable
Discrete	Equally likely over values
Continuous	Useful as an alternative to a theoretical distribution that has been fitted to the data, such as in data that have a multimodal profile or where there are significant outliers
Erlang	Service times, multiple phases of service with each phase exponential
Exponential	Time to perform a task, time between failures, distance between defects
Gamma	Repair times, time to complete a task, replenishment lead time
Lognormal	Time to perform a task, quantities that are the product of a large number of other quantities
Poisson	Counts of occurences in an interval, an area or a volume

Triangular	Rough model in the absence of data assume a minimum, a maximum, and a most likely value
Uniform	When you have no data, everything is equally likely to occur within an interval,machine task times
Weibull	Time to failure, time to complete a task

B-1.12. Goodness-of-Fit Tests

Once the modeller decides on a distribution, next step should be the goodness of fit test to ensure the selected distribution represents the data correctly and good fit. These tests provide help for the beginning, but they are only for guidance. In reality, there is no single correct distribution. Therefore, the answer from these test should not be regarded as the only correct solution (Banks, 2005).

B-1.12.1. Chi-Square Test

Chi-square test is the most common goodness-of-fit test and can be used to test both discrete and continuous distributional assumptions. Chi-square test is used to confirm the null hypothesis (H_0) which is "the data (sample size n of random variable X) comes from the specified distribution". The alternative of the null hypothesis for the Chi-square test (H_1) is that the data does not fit with the specified distribution. Chi-square test requires a large sample size in order to be valid. First, n observations are arranged into a set of k class intervals (or cells), and the test statistic is given through (Banks, 2005);

$$X_0^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

O_i is the observed frequency

E_i is the expected frequency (E_i=np_i, p_i is theoretical hypothesised probability)

Text statistic X_0^2 approximately follows the chi-square distribution with k-s-1 degree of freedom (number of parameters of the hypothesised distribution estimated by the sample statistics) (Trimbitas, 2010). The critical values for

$X_{\alpha,k-s-1}{}^2$ can be found in Banks' book (Banks, 2005). H_0, the null hypothesis is rejected if $X_0 > X_{\alpha,k-s-1}$.

For discrete data case, there is no need to combine adjacent cells;

$$p_i = p(x_i) = P(X = x_i)$$

If the distribution is a continuous distribution, (class intervals are the endpoints; ai-1, ai) and p can be calculated through

$$p_i = \int_{a_{i-1}}^{a_i} f(x)dx = F(a_i) - F(a_{i-1})$$

B-1.12.2. Kolmogorov-Smirnov test

Kolmogorov-Smirnov test is also used to decide if a sample comes from the specified distribution but different from the Chi-square test, it can only be used for continuous distributions. Kolmogorov-Smirnov test is a particularly strong test when the sample sizes are small, and there are no parameters that have been estimated from the data (Banks, 2005).

Kolmogorov-Smirnov test compares the continuous cdf (F) with empirical cdf (S).

$$S_N(x) = \frac{no\ of\ R_1, R_{2,}\ R_N}{N}$$

The first step of the Kolmogorov-Smirnov test is to rank the data from smallest to largest then compute the Deviation D= max(D^+,D^-). D^+ and D^- are calculated;

$$D^+ = max_{1\le i\le N}(\frac{i}{N} - R_i)$$

$$D^- = max_{1\le i\le N}(R_i - \frac{i-1}{N})$$

Once the D is calculated, it needs to be compared with critical value D_α through the Kolmogorov-Smirnov Critical Values table (can be found in (2005)). If the D calculated is bigger than D_α, the hypothesis is rejected and if D is smaller than D_α means that there is no difference between the distributions.

B-1.12.3. p-Values and best fit

In order to apply a goodness-of-fit test, a significance level must be chosen. The significance level is the probability of falsely rejecting the null hypothesis (Banks, 2005). Most important part of the goodness-of-fit test is that p-value is always between 0 and 1 and p values over 0.05 (0.1 and 0.01 are the other common significance levels) means the null hypotheses is accepted and if the p-value is 0.05 or less the null hypothesis is rejected (means the distribution does not match the actual distribution).

Majority of the DES software calculates the p-value automatically through the built-in tools and guides the user with the best fit. In the next section, simulation tools will be investigated and a simulation tool that is suitable for ship recycling will be selected.

B-2. ARENA Discrete Event Simulation Software

This section briefly introduces the “Arena Discrete Event Simulation” software. Arena simulation sold and distributed by Rockwell Automation. As a software, Arena has been used commonly for academic and industrial purposes. The Arena is based on SIMAN simulation language, and the modules in the Arena were created using SIMAN’s modelling blocks (Takus and Profozich, 1997). In this thesis, Arena version 15, which was released in December 2016, was used.

The user manual of the Arena (Rockwell Automation, 2010) is very detailed, and all the properties of the software are introduced in the manual. Apart from the manual, Arena has built-in examples and SMARTs library to help the user from the start as well as online help.

The user interface of Arena is straightforward and comprises of three main sections; project bar and model window which separates into flowchart and spreadsheet windows (Figure B.12).

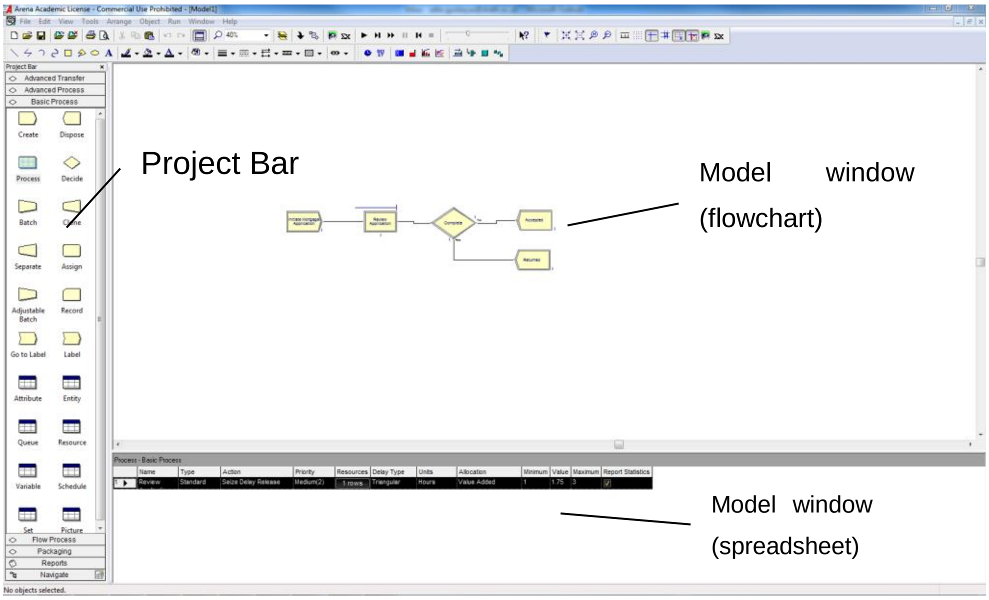


Figure B.12: ARENA Interface

Modelling simulation system is straightforward; relevant modules are dragged to the model window (flowchart) from project bar (Figure B.13), and details can be entered through both flowchart and spreadsheet window. For arena, modules are the objects that define the process to be modelled and simulated (Rockwell Automation, 2010)

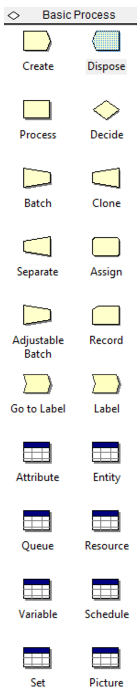


Figure B.13: Project Bar

In the project bar, there are two different module types: flowchart modules and data modules. Main flowchart and data modules were introduced below(Rockwell Automation, 2010).

First, the flowchart modules are summarised. Even though the flowchart modules are not limited by these, the ones introduce in here are the major ones that can be used to model most operations.

B-2.1. Flowchart Modules in Arena

Create Module (Figure B.14) starts the process flow, in other words, entities enter the simulation system through create module with specific or random intervals (time between arrivals) and numbers (entities per arrival).

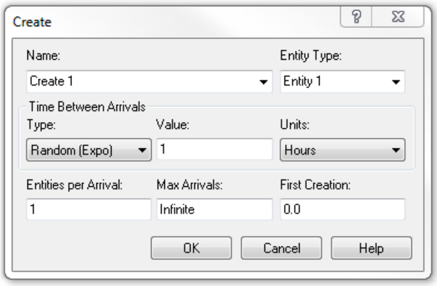


Figure B.14: Create module

The example uses for the ship recycling simulations could be;

- the arrival of the end of life ship,
- block entering a secondary cutting zone or
- dismantled materials are entering the segregation zone.

Dispose Module (Figure B.15) ends process flow. Through the dispose module, entities are removed from the simulation system. All entities that go through the dispose model are removed from the model.

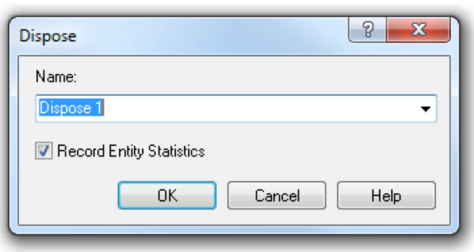


Figure B.15: Dispose module

The example uses for recycling yards are

- parts leaving the yard to a steel mill,
- hazardous material leaving the system for treatment or
- blocks are leaving the primary cutting zone.

Process Module (Figure B.16) is the primary processing method of the entities through an activity (that is requiring resources and takes time to complete) with allocated logic (delay, seize delay or seize delay release) and defined delay time.

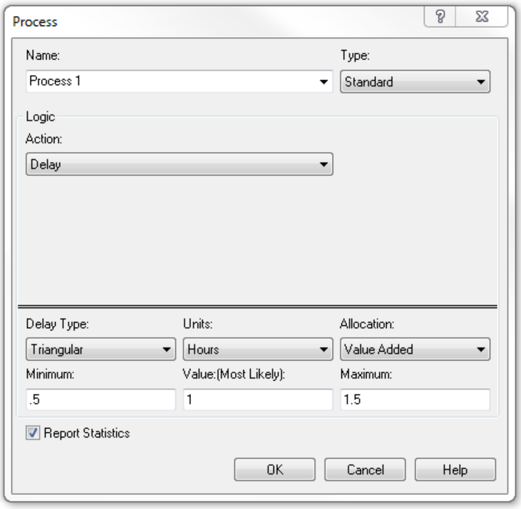


Figure B.16: The Process module

Example uses of a process for the ship recycling models are

- hazardous material treatment from the ship,
- ships arrival to yard and beaching,
- cutting process and
- safety inspections.

Decide Module (Figure B.17) divides the process through a branch to a number of directions input by the user. Entities go through the branch according to a condition defined by the user. Example uses of deciding module in the ship recycling models are

- a decision on which quay ship will go to
- rejection of ship

- a decision on which zone the part/block will go

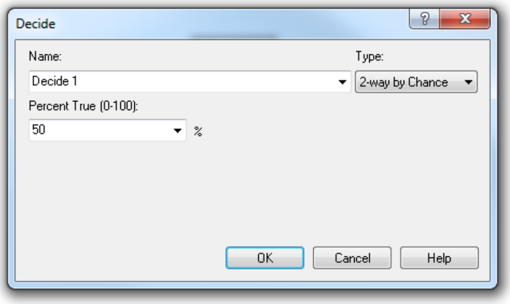


Figure B.17: Decide module

Batch Module groups entities (permanently or temporarily) with specified numbers before they continue the flow in the model (Figure B.18). Grouped entities act as a single entity until separated or exit the system.

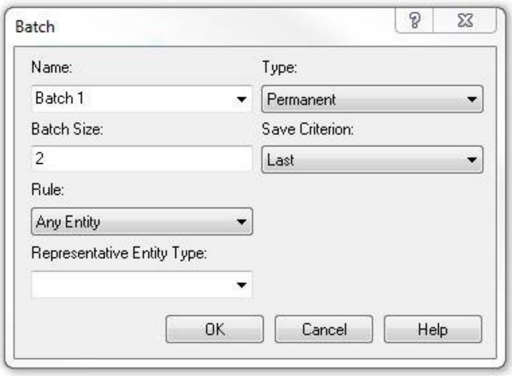


Figure B.18: Batch module

- Permanently storing the materials before transportation
- Removing processed material from the yard as a pack

Separate Module, on the other hand, can separate the batches formed by the user, and it can duplicate the existing entities for parallel processing.

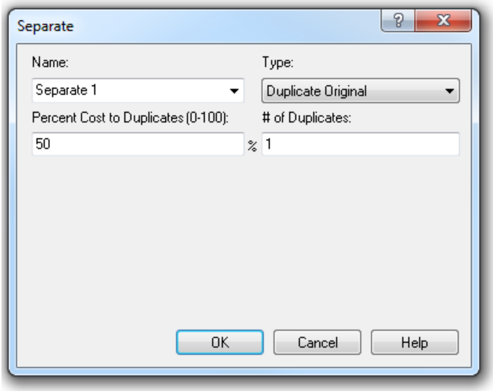


Figure B.19: Separate module

Example uses of the separate module for recycling simulations are

- Separate previously grouped materials
- Separate cut blocks from ship or
- Separate cut panels from blocks

Assign Module changes the attributes or variables in the simulation. Through the assign module, existing parameters can be altered or new parameters, e.g. picture can be assigned to entities.

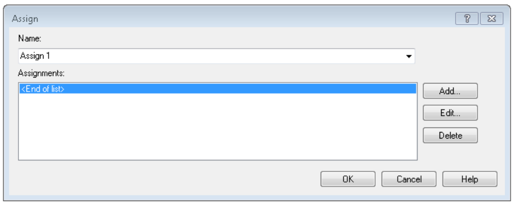


Figure B.20: Assign module

Assign can be used in recycling models to

- Assign pictures to ships, parts, blocks
- Assign process (cutting, lifting, transport) times to blocks/parts
- Change a process' or entity's priority

Record Module collects statistics (time, cost, number and so forth) of the entities pass through the module.

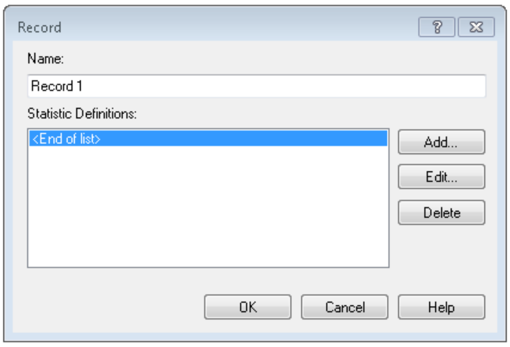


Figure B.21: Record module

The example uses for the record are

- Total number of processed parts,
- Total time in the simulation
- How many parts are taking more time to process than the average?

B-2.2. Data Modules in Arena

In addition to the flowchart modules, there are also data modules as mentioned above. Similar to the flowchart modules, not all the data modules but the important ones are covered.

Entity module (Figure B.22) describes the type and properties of the entities in a simulation model.

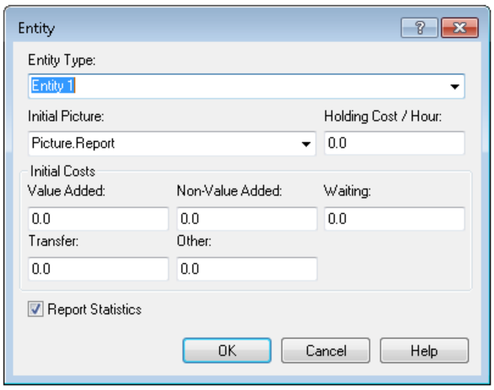


Figure B.22: Entity module

The entity in a ship recycling model can be

- Ship
- Blocks
- Plates
- Hazardous materials

Queue module (Figure B.23) defines the logic in the queue of the model. Depending on the model and operation, different type of queues like “First-in, First-Out”, Last-in, Last-out” or “Lower/Higher attribute first” can be set. Unless stated, Arena uses First-in, First out rule as default.

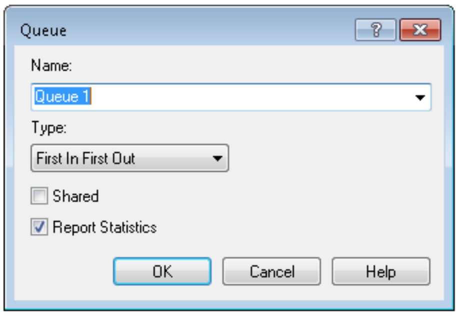


Figure B.23: Queue module

Examples for the ship recycling are

- The secondary zone that blocks waiting to be cut,
- processed materials waiting for transport or
- storage area for the segregated material.

Resource module (Figure B.24) defines the properties (cost, capacity, availability type (fixed or schedule), failures if they exists) on the resource to the simulation model. As a default, Arena takes resource number as “1” unless stated.

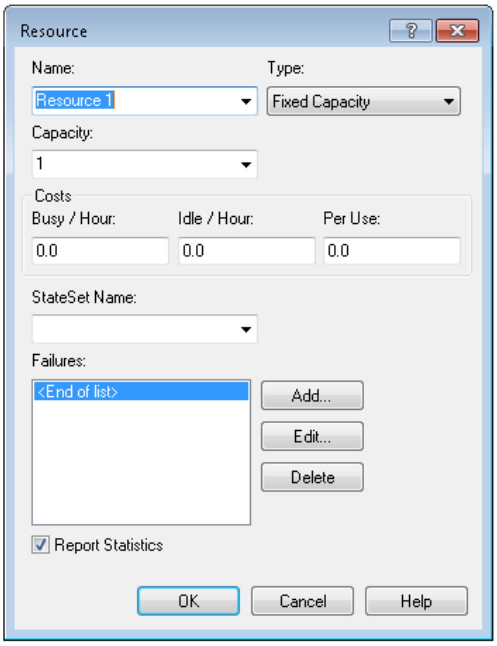


Figure B.24 The Resource module

Resources in a ship recycling model can be

- Workers/Operators
- Cranes/Winches
- Torches/cutting machines
- Trucks/drivers

Variable module (Figure B.25) defines variables with dimensions and values, which can be used in other modules (decide, process, expressions). Variables can have different values in the same model using the Assign module.

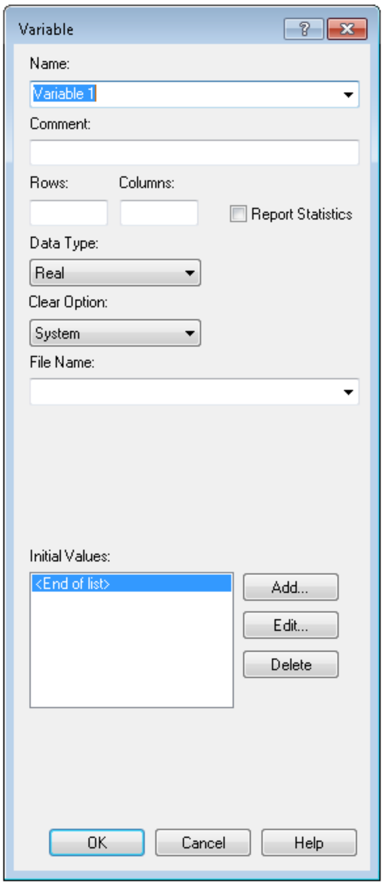


Figure B.25: Variable module

Examples of variable use in ship recycling yard are

- Space available in the secondary cutting zone,
- Number of blocks that can be handled in a day,
- The capacity of the quay

Schedule module (Figure B.26) is used to define custom schedules to resources or entities. Schedules can be created to define the shifts for the resources (workers, machines, or space) or to use different arrival times for the entities (customers arriving in the bank in different numbers throughout a day).

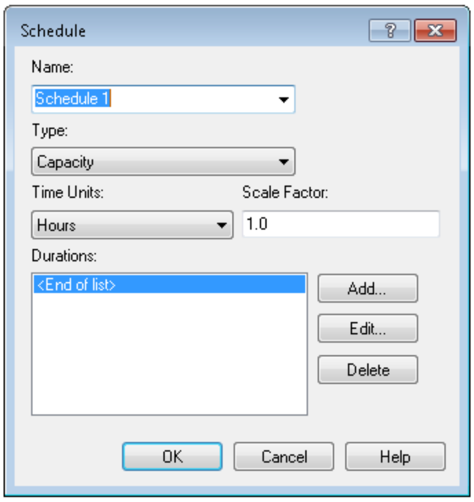


Figure B.26: Schedule module

The schedule can be used in models to

- Organise the working schedule of workers
- Organise the availability of equipment
- Model the breakdown of equipment

Set module (Figure B.27) defines a different type of sets (resource, counter, entity) to form a group which can be used in process modules.

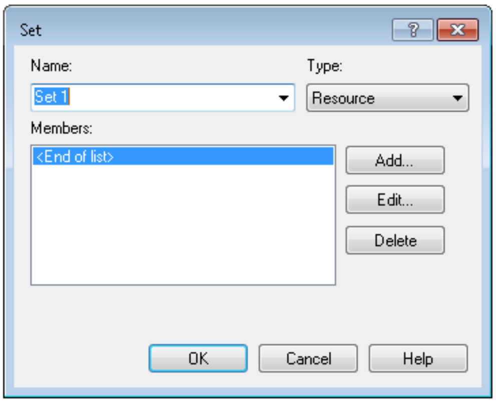


Figure B.27: Set module

The example uses in the yard models are

- Cutting torches or surface treatment machinery
- Cutters and helpers
- Blocks of a specific part of the ship (e.g. double bottom)

More of the modules will be shared in Chapter 5 of this thesis where the ship recycling modelling framework was introduced. In the next section, a simple Arena model for a secondary cutting zone will be shown as a demonstration of modelling in Arena. This section is inspired by the tutorial in Arena's manual (Rockwell Automation, 2010).

B-2.3. Simple Arena Model in Secondary Cutting Zone

In this section, a simple Arena model will be shown to demonstrate how to model in Arena Simulation Software. Secondary cutting zone in a hypothetical ship is modelled in this demonstration simulation. In this scenario, a block (cut from the accommodation area of a ship) is transferred to the secondary zone from the primary cutting zone. In the secondary cutting zone, the block will be cut to further pieces and segregated further according to the material type of the block. For this scenario, 90% of the incoming material is steel and %10 is stainless steel. Steel parts are stored for transport and stainless steel parts stored in the yard. The model of the process is shown in Figure B.28.

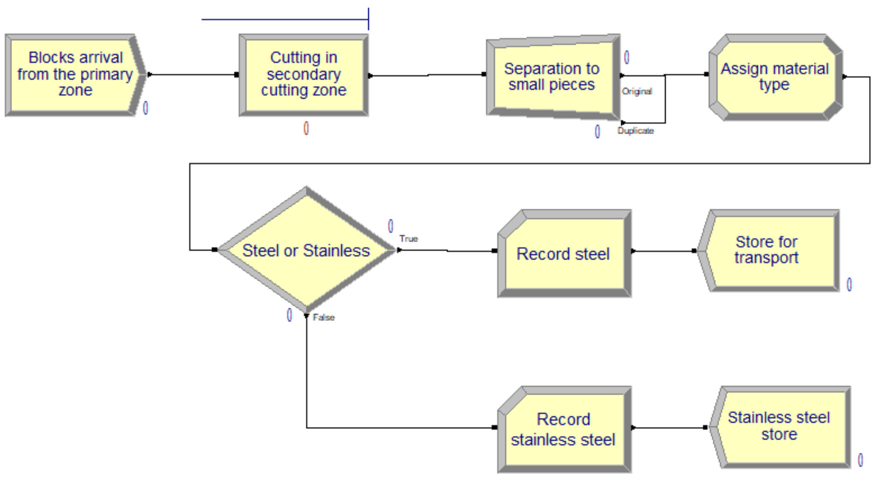


Figure B.28: Overview of the Arena model

The first step of the modelling in Arena is creating the entities and module used to create the entities to the system is **Create** module, namely "Blocks arrival from the primary zone" in Figure B.28.

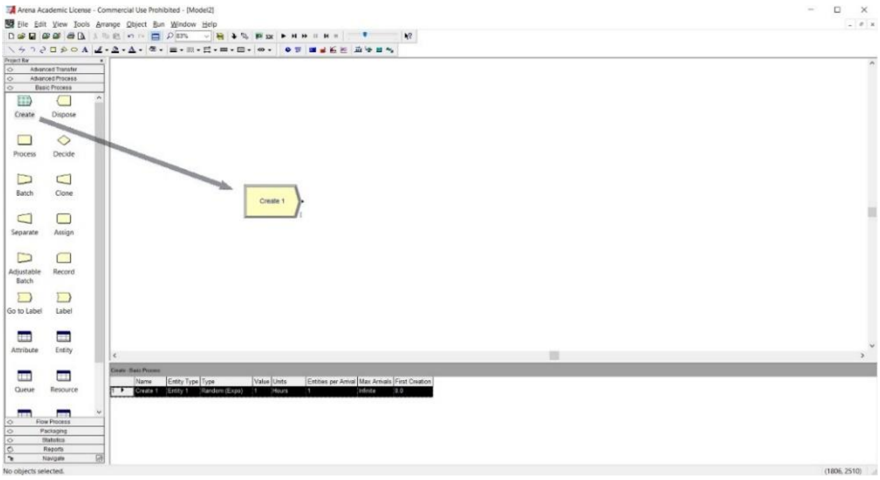


Figure B.29: Create module, drag and drop

The properties of the create module can either be modified from the spreadsheet view or by double-clicking the module in the flowchart view (Figure B.30). Name of the module (Blocks arrival from the primary zone), Entity type (Accommodation Block), the time between arrivals, entity per arrival and maximum arrival can be changed from this dialogue box.

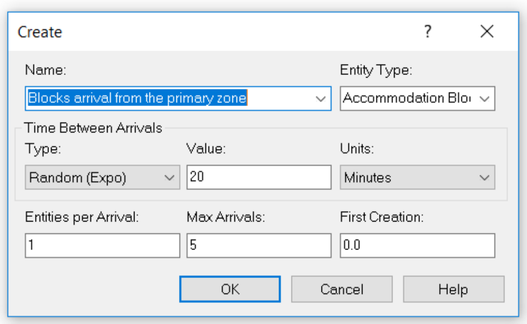


Figure B.30: Properties of create module in the model

For this simple model, the initial assumption was the blocks coming from the primary cutting zone every 20 minutes with exponential distribution. Also, it was assumed that only one block would come each time to the maximum of five blocks.

After the creation of the blocks or in other words entities, the next step is the cutting process. Therefore, a **Process** module follows the create module (Figure B.31).

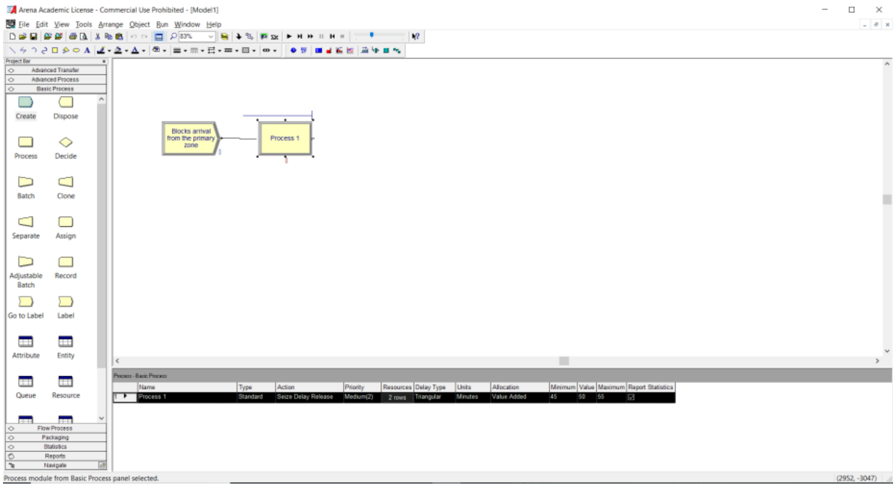


Figure B.31: Connection of the process module

Similar to the create module, process module is also dragged and dropped to the workspace. Arena automatically connects the modules as shown in Figure B.31. There is a manual connection option in Arena as well. Similar to the Create module, Process module can be modified through the dialogue box (Figure B.32).

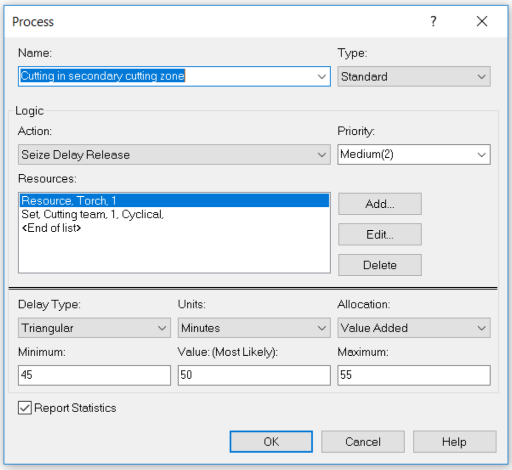
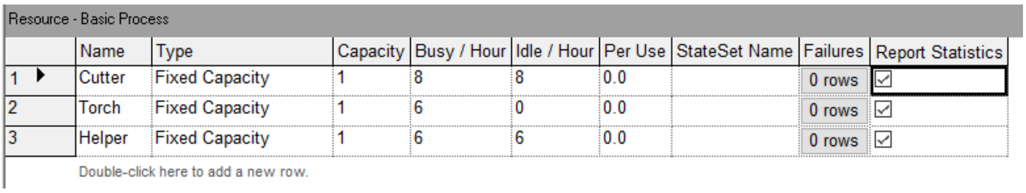


Figure B.32: a Process module

In this model, the action type was selected as “Seize Delay Release”, which will seize the defined resource, delay it according to the delay type and duration, and then release it. As a resource, Two different resource types were set; torch as resource and cutting team (cutter and helper) as resource set. Details of these resources can be altered through the spreadsheet view of the resource (Figure B.33). Capacity (number of workers), costs when busy and idle or costs per use can be altered through this spreadsheet.



Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	Cutter	Fixed Capacity	1	8	8	0.0		0 rows	☑
2	Torch	Fixed Capacity	1	6	0	0.0		0 rows	☑
3	Helper	Fixed Capacity	1	6	6	0.0		0 rows	☑

Double-click here to add a new row.

Figure B.33: Resources spreadsheet

The time for delay, triangular distribution was used in this example as it provides a good approximation (Rockwell Automation, 2010). In the triangular delay type, minimum, most likely and maximum duration of a process are input to the simulation model. Distribution of the simulation run after repetitions would look like Figure B.32 (Rockwell Automation, 2010)

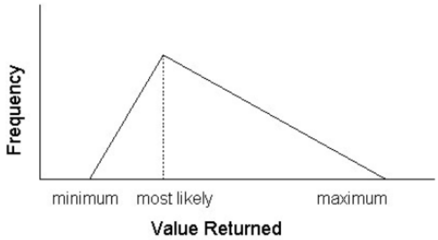


Figure B.34: Frequency and returned value graph for triangular distribution (Rockwell Automation, 2010)

After the cutting step, blocks are separated into small pieces according to a steel mill's standards. In order to divide the entity to small pieces a **Separate** module was used. The separate module was used to clone the initial entity into the smaller plates. In this case, some duplicates between 50 and 100 were input to the system with uniform distribution.

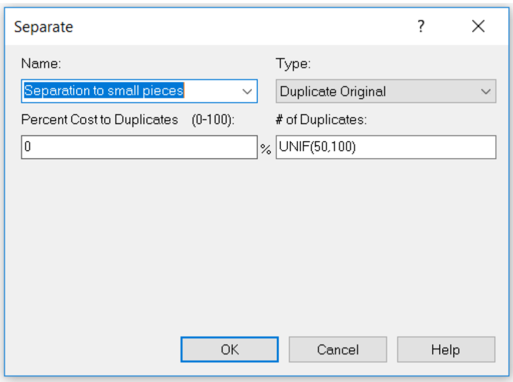


Figure B.35: Separate dialogue box

Following the separation, an **Assign** module randomly assigns a material type to entities with 90% of them being steel and 10% of them being stainless steel. This assignment is done through the DISC(0.9, 1, 1, 2) which means 90% (0.9) of entities will be type 1 and remaining to 100% (1) will be type two.

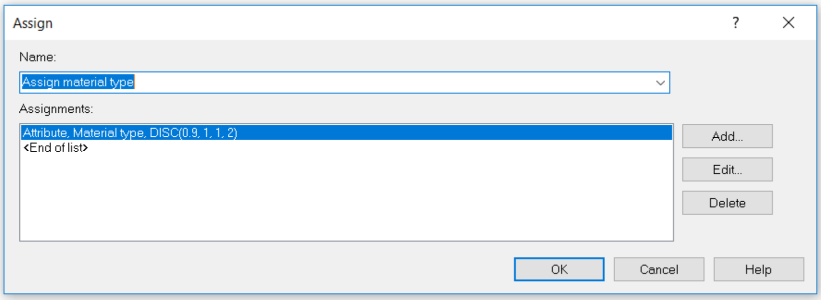


Figure B.36: Assign dialogue box

After the Assign model, **Decide** module is used to redirect the steel to storage for transport and stainless steel for storage in the yard according to their attributes. In this decide module, if the material type attribute is equal to “1”, the process flow is directed to the True branch (Figure B.28), and if it is not 1, it is directed to “false” branch.

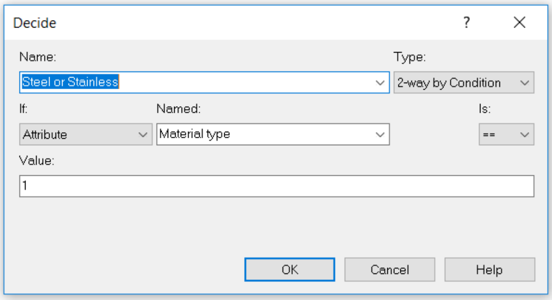


Figure B.37: Decide module

After entering their branches, entities go through the **Record** modules to count the number of parts leaving the system. Following record modules, both entities leave the system through the **Dispose** modules.

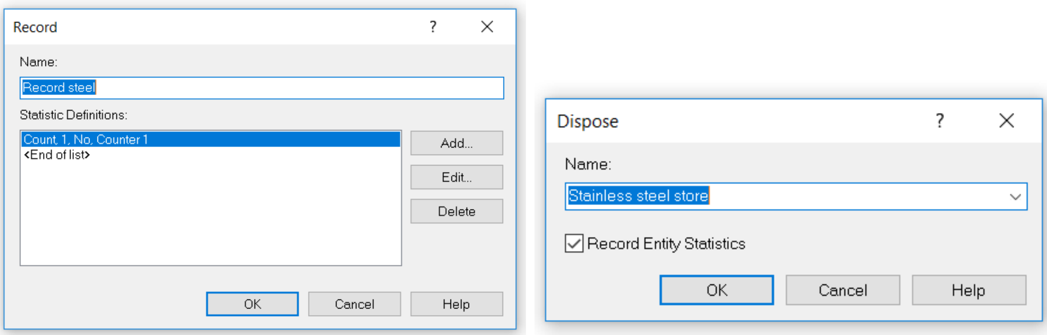


Figure B.38: Record and Dispose modules

After completing the modeling, the next step is the preparation for the simulation. Run setup is accessible through Arena's menus and the run setup, replication parameters, run speed, reports or project parameters can be arranged. For this simulation, ten replications will be done.

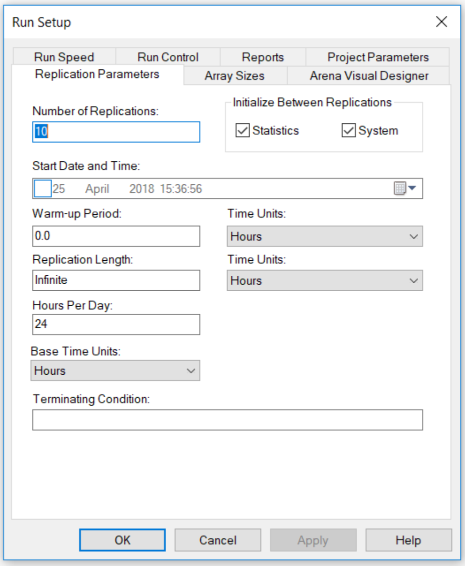


Figure B.39: Run setup dialogue box

Once the simulation starts, the system animates the entities in an elementary form to inform the modeller on the basic details of the simulation. If any interface is not set, Arena informs the user of variable changes through the flowchart view. The speed of the simulation process can be increased or decreased through Arena's interface.

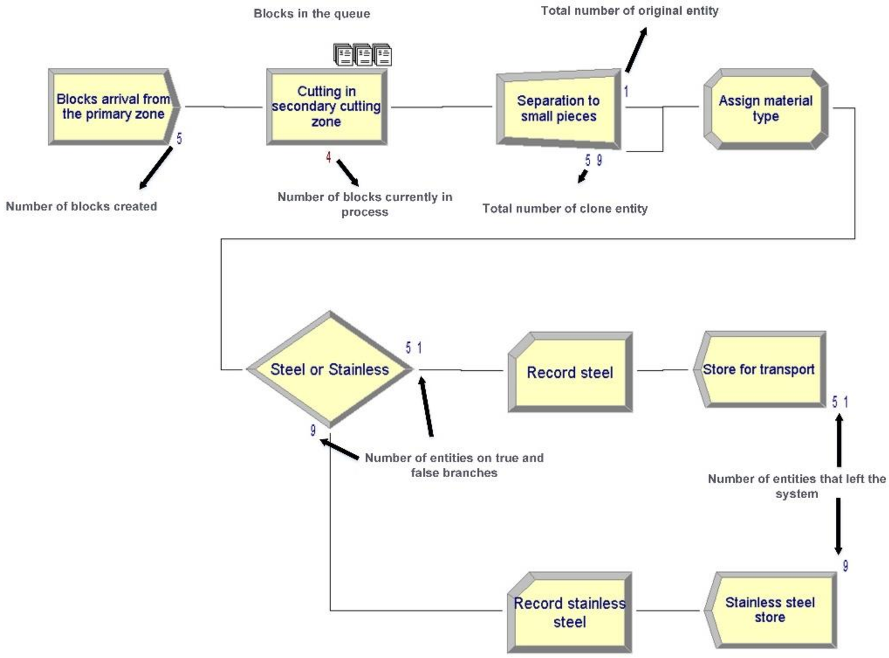


Figure B.40: Simulation in progress

Once the simulation run is completed Arena automatically generates a report. This report covers the selected parameters such as cost, number of entities out, resource utilisation, queue times, process times and so forth. The report can be seen in Figure B.41. In this report, specific sections can be accessed through clocking the tree on the left side. The overall report answers the questions like “what is the average time to complete a block’s cutting?” (50.2 mins), “what is the total cost of the operation?” ($84), “what is the total number of plates leaving the system?” (396), “total waiting time in the system” (67 mins average per repetition), “what is the utilisation rate of resources?” (100% for this specific case). Both results and simulations can be improved with animations, graphs, additional analysis through the Arena software.

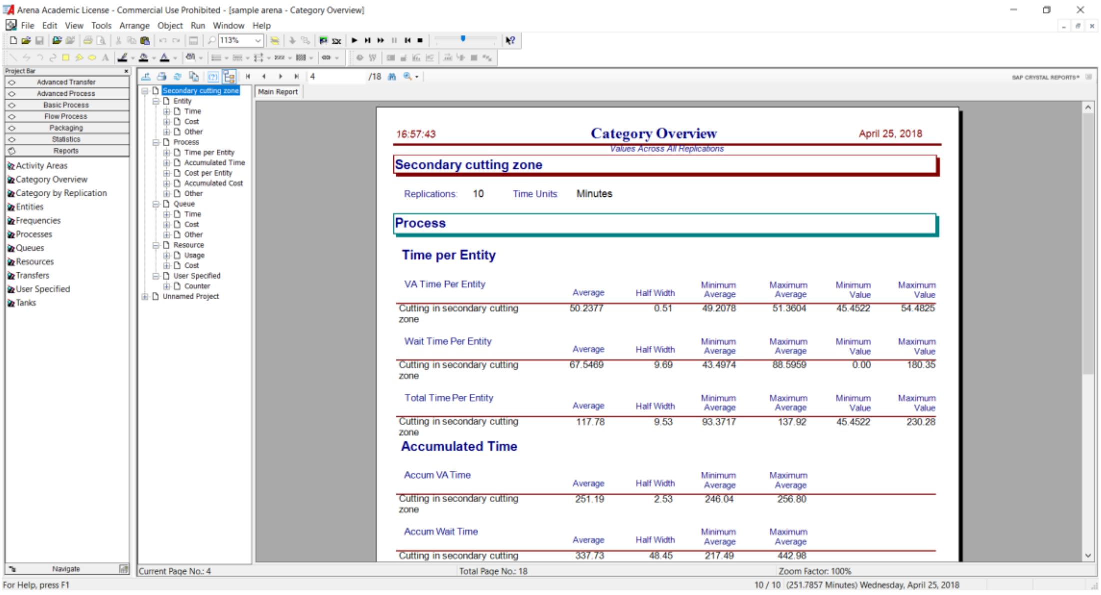


Figure B.41: Arena result report

In this section, a straightforward Arena simulation for a ship recycling yard is demonstrated. In the example, Arena modules were introduced and the options summarised. In some of the modules, distributions were used instead of deterministic values. In the simulation, when an entity enters the process (or relevant module) Arena calculate a sample from the distribution information provided by the user (Rockwell Automation, 2010). In this simulation, only three, Triangular, Uniform and Discrete, distributions were used. In order to understand Arena and the simulation methods, detailed information on distributions will be given in the next section.

B-3. Simulation Model for Ship Recycling Yard Operations Using Arena

This section describes the development of a simulation model of a ship recycling system based on a generic ship recycling process model developed in this chapter. The representation of this flow process in the Arena environment is shown in Figure B.42. In order to simplify, the processes are shown as sub-models in the below figure. Each module within these sub-models will be explained in the following sections.

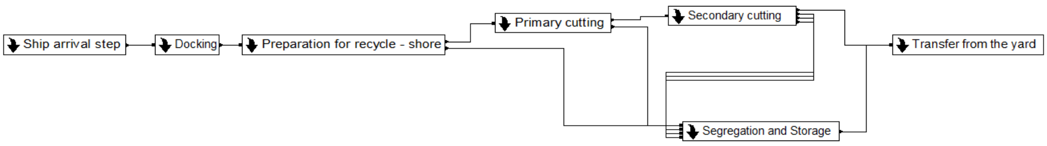


Figure B.42: Arena representation of the simplified flow process using the sub-model logic

B-3.1. Ship Arrival Step

Ship arrival step represents the introduction of the ship to the system. In this step, ships that will be processed will be introduced to Arena Environment, Assigned properties and will be sent to decide module to be processed further. Model representation and arena model of this step are given in Figure B.43.

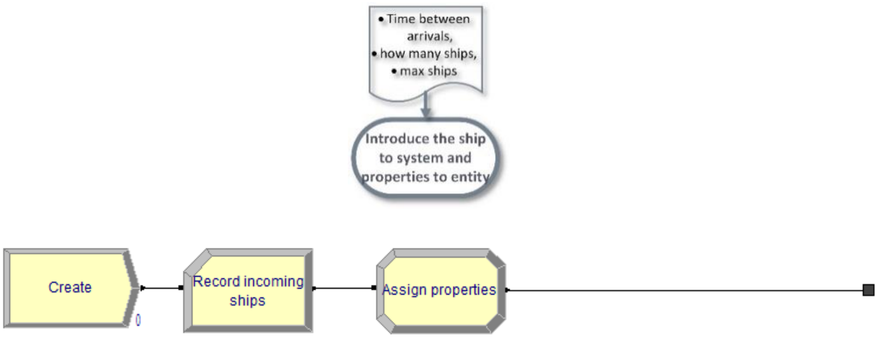


Figure B.43: Ship arrival step graphical representation (above) and translated to the Arena environment (below)

In the Arena, "**Create**" module represents the arrival of the ship (Figure B.44). In this module, the entity type is given as a ship in the example in Figure B.44, but in the case of several ships to dismantle, different names for entity types can be used. The time between arrivals (value) will be used to input the ship arrivals to yard (could be based random (expo), depending on schedule, constant or expression). Entities per arrival are used to input the number of ships created in the system while Max Arrivals shows the maximum number of ships to be dismantled through the simulation run.

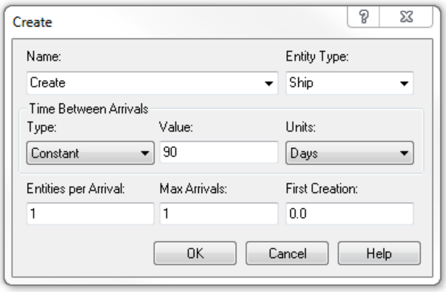


Figure B.44: First step of the simulation, creating the ships.

Following the create module Arena's other logic modules such as "**Record**" module to count the number of incoming ships or other properties (Figure B.45). Figure B.45 represents an example use of record which counts the number of ships entering the system. This module might come in handy in complex simulations where there are more than one entity, ship, enter the system.

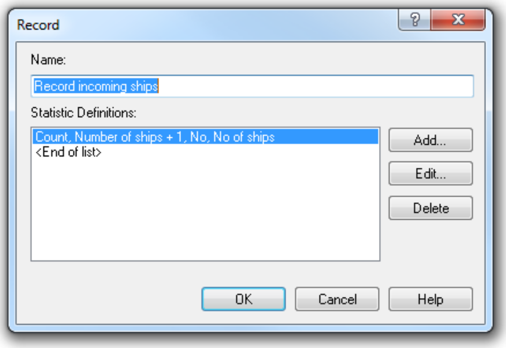


Figure B.45: Record module use to count the number of ships entering the system

In addition to these modules, "**Assign**" module can be used to assign properties (attributes, variables, entity types, entity pictures) to the entities. In the example shown in Figure B.46. Apart from the uses in the example below, operation times in different areas/zones can be defined at this step and can be used as "Expression" in the "Process" modules.

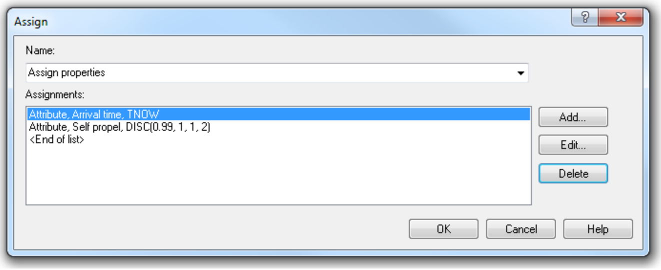


Figure B.46: Example of "Assign" use in Arena

Table B.4.: Data to collect and resources involved for the ship arrival step

Data to collect	**Resources involved**
Ship arrival times Maximum ship arrival for the simulated period Assumptions if any will be made on the ship type, ship's condition, IHM necessity and so forth	

B-3.2. Docking

Once the ship arrives at the yard, the next step is the docking of the ship. During the docking of the ship, depending on the ship's condition (whether it can self-propel or not), tugboats can be included in this step. For the generic simulation, tugboats are not included in this step, but the additional process can be added to this step for the arrangement of tugboats and pulling the ship with tugboats.

The generic process of docking of the ship is summarised to two steps; docking of the ship and securing the ship and arranging access. Graphical representation and Arena modules for this step are shown in Figure B.47.

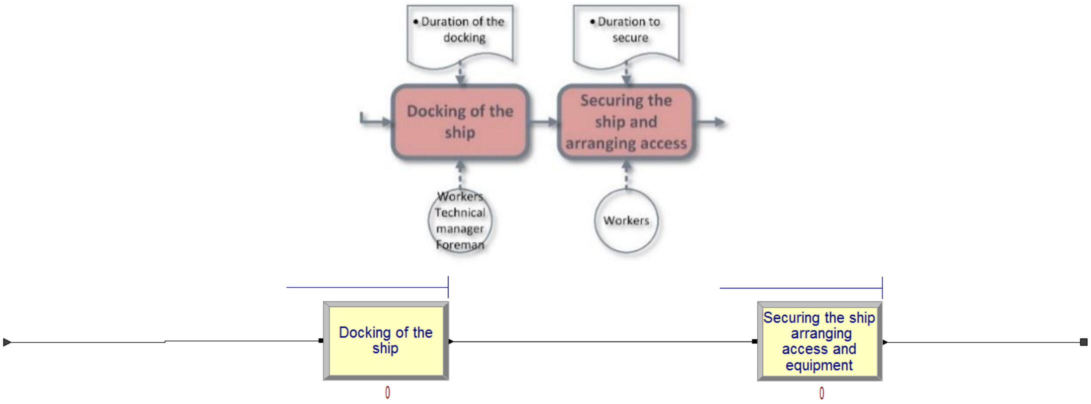


Figure B.47: Docking step graphical representation (above) and translated to the Arena environment (below)

Two different Arena Process modules were envisaged for this step; "Docking of the ship" and "Securing the ship, arranging access and equipment". Depending on the analyst, these steps can be combined.

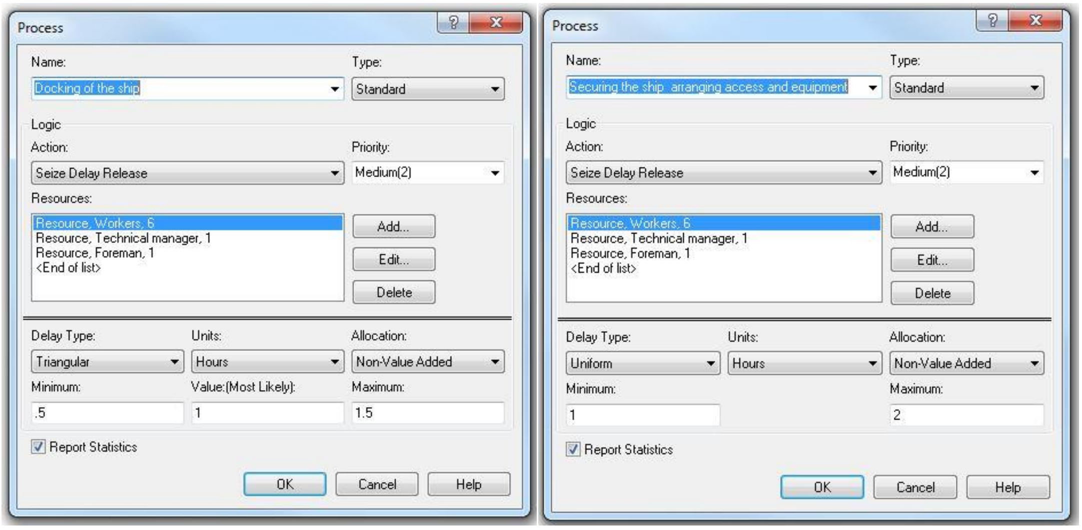


Figure B.48: Use of Process modules to model the docking and securing steps

Process step in Arena has four different logics; Delay, Seize Delay, Seize Delay Release and Delay Release. For both processes, “Seize Delay Release” logic has been selected which means for this job, process module will seize the required resources, hold them during the delay duration (the duration of docking) and will release the resources when the process is completed. Priority of the process is set to medium but can be set to “High” or “Low” depending on the analyst’s choice. As the priority of a process increases, programme puts the process with higher priority in front of other processes with lower priority.

Resources to be used in the process are also added through the **Process** module along with the number required for the process. Next, the delay type is set for each process along with units. As a default, Arena offers four different distributions (Constant, Normal, Triangular, and Uniform) but additional distributions can be introduced through the “Expression” and “Expression Builder”. Through the allocation drop-down menu, type of the allocation (“Value-added”, “Non-value added”, “Transfer”, “Wait” and “Other”) can be selected. Allocation options do not affect the simulation; it only categorises the results of the processes according to the type selected. In order to build this step of the simulation, required data and resources involved is listed in Table B.5.

Table B.5: Data to collect and resources involved in the docking step

Data to collect	**Resources involved**
Duration of the docking Duration to secure the ship, arranging access and equipment	Workers, Technical manager Foreman

B-3.3. Preparation for recycling – shore

After the docking and securing the ship, the ship is prepared to recycle in the yard. In this step, IHM survey is conducted if necessary, the ship is inspected for safety, general cleaning of the hip is conducted, hazardous materials are removed from the ship, liquid waste is removed, and finally quality check is done to ensure all the hazardous waste is removed from the end of life ship. The last step is the check of the authorities before starting the cutting procedures. The graphical representation and Arena submodel of this step are shown in Figure B.49.

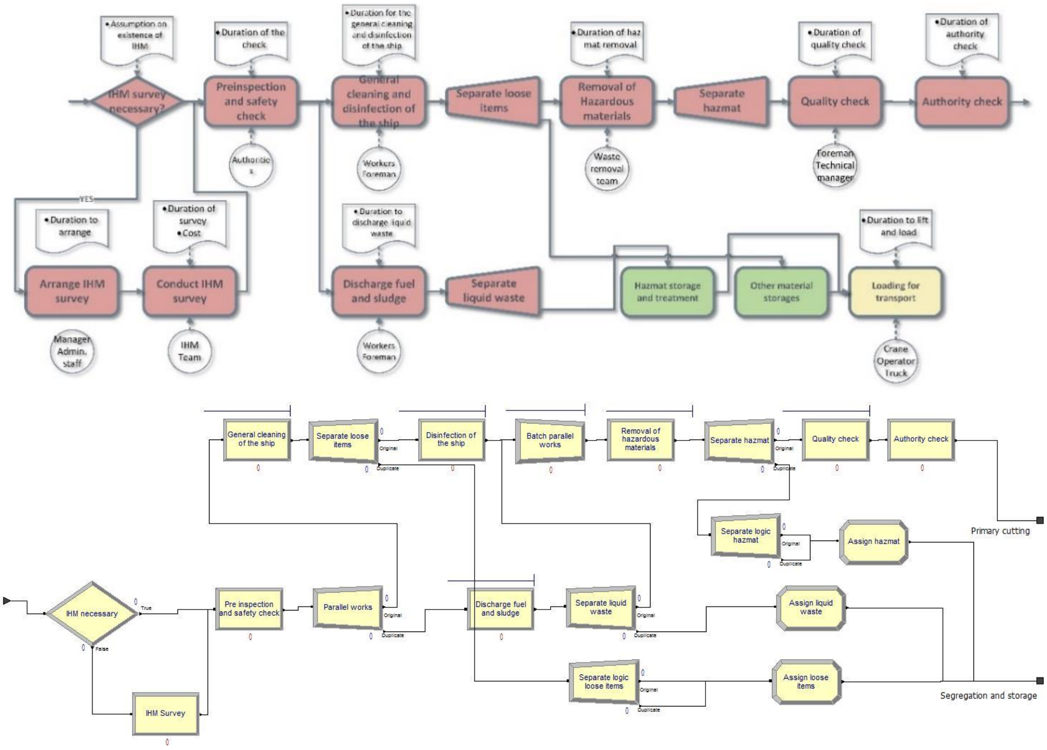


Figure B.49: Preparation for recycled step graphical representation (above) and translated to the Arena environment (below)

The Arena model shown in Figure B.49 first decides if the IHM survey is necessary. In this example, simulation defines the IHM necessity through probability and with 90% chance IHM is required. In this case entity goes through “IHM Survey” process module if IHM is required (Instead of chance, this can be defined through “Create” and “Assign” modules in the ship arrival step if required). For this case, it was assumed that the IHM survey would be conducted by an external company. Therefore, no resource was involved in the process module. As a result delay logic is used with a delay time (Figure B.50).

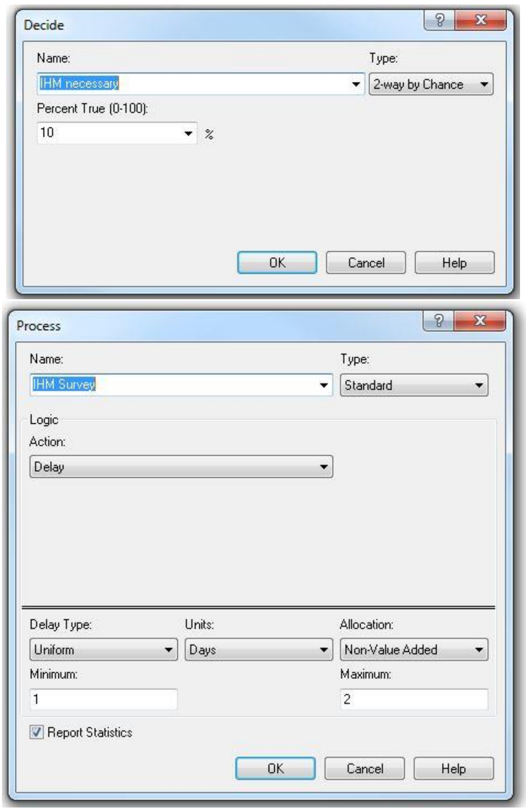


Figure B.50: Use of Decide module to define IHM survey necessity and use of Process module to model IHM survey

Following the IHM survey, “Preinspection of the ship and Safety Check is conducted by authorities, before starting any dismantling operation. Since an external body conducts this, it can be modelled with a Process module with Delay logic, or directly with a Delay module from the Advanced Process template of Arena. Once this inspection is completed, general cleaning and disinfection of the ship start. This step is represented by a Process model as shown in Figure B.51. In parallel to the cleaning, fuel and sludge of the ship can be discharged (which is also represented with process model) and the waste send to storages (Figure B.51).

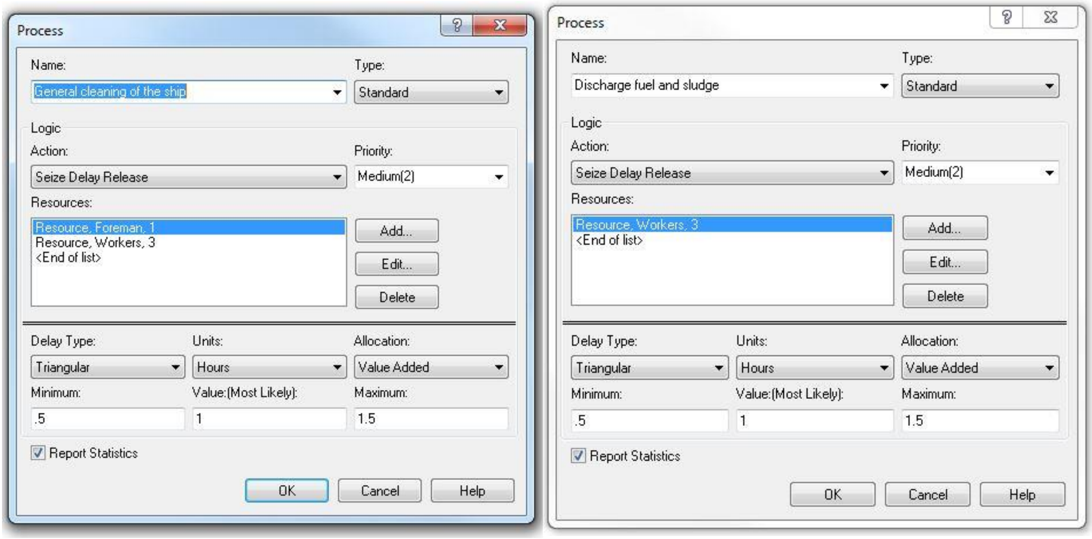


Figure B.51: Process modules for general cleaning and discharge of fuel and sludge

In order to create the logic of the parallel work in Arena, the **Separate** module is used in the model Figure B.52. The separate module has two different types; Split existing batch and Duplicate original. Split existing batch, splits the entities that are combined using the batch command while Duplicate original copies the original entity to the number of entities selected by the modeller. Percent cost to duplicates option should be zero for parallel works as it is the cost to create the duplicate.

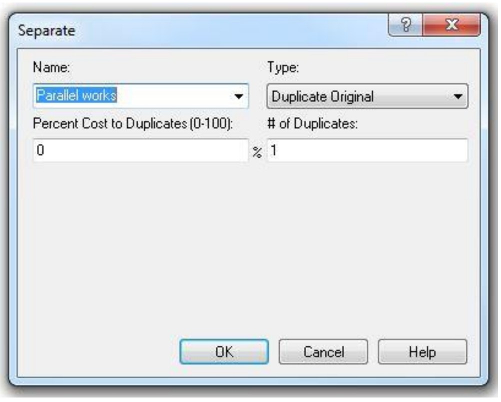


Figure B.52: Separate module in Arena

Another common use of the **Separate** module in the ship recycling simulation approach is to create the material, equipment, parts or waste and separate them from the primary entity. The example of this use is shown after the general cleaning of the ship module, where the loose items are removed from the ship after the general cleaning Figure B.53.

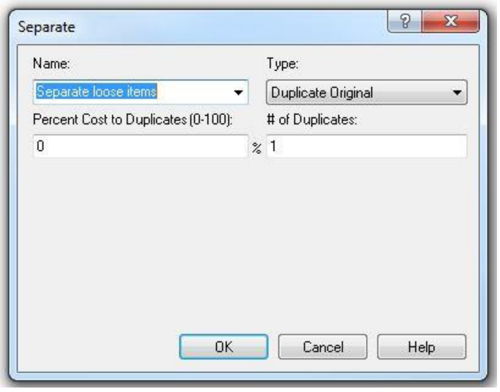


Figure B.53: Separate module for removing material/waste from the ship.

However, a separate module creates in this instance only one duplicate which is not realistic considering the amount of material that will be removed from the ship. Therefore, the separated entity is connected to another separate module to accurately model the number of items removed from the ship at this stage Figure B.54. Two different data is needed in order to define the number of duplicates; one is the capacity of the yard's crane or lifting equipment and the other is the weight distribution of the ship for different weight categories. A good reference point to allocate the weight distribution and material flow from the ship is the study of Jain (2017). More detailed application of the separate and the creation of duplicates using the material flow is demonstrated in Chapter 6 of this study.

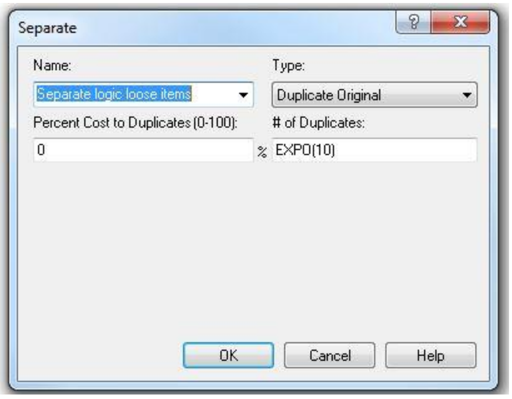


Figure B.54: Separate logic to create entities

After the separation and creating the duplicates, the materials should be categorised according to the material type. For convenience, an attribute called “Material Index” is created for the simulation model (Figure B.55).

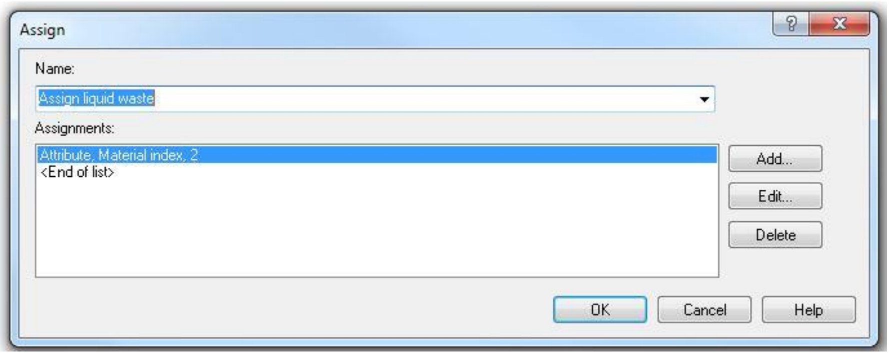


Figure B.55: Assign use to allocate “Material Index” to separate items

All material types are allocated with a number (Table B.6) which is later used by the Decide module in Segregation, Hazmat Treatment and Storage submodel according to the Material index and directed to the appropriate module. The “Separate” and “Assign” logic also used for liquid waste and hazmat in this submodule to separate these later.

Table B.6: Material type and Material index allocated

Material/equipment type	Material index
Loose items	1
Liquid	2
HAZMAT	3
Insulation flooring tiling	4
Cables and electrical equipment	5
Machinery	6
Steel	7

Sometimes it is required to finish all the processes in progress in order to start the next one. It was assumed that disinfection and liquid discharge need to be finished to start the removal of the hazardous material process. These two processes were designed as parallels, and the Separate module was used to create the logic. In order to reverse this and to combine the parallel processes, the **Batch** module is used (Figure B.56).

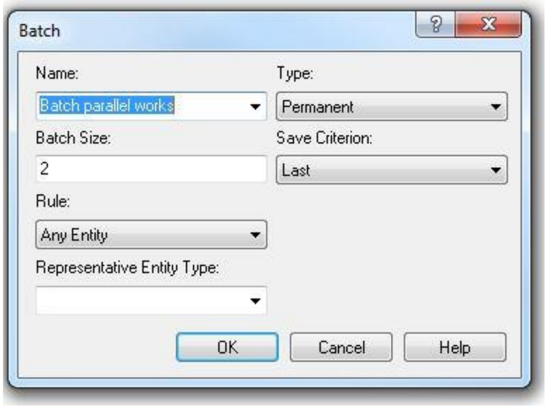


Figure B.56: Batch use to combine different branches

The batch module has two different types: Permanent and temporary. As the names suggest, permanent batches cannot be separated later while the temporary batches can be separated. Batch size is set to “2” as two parallel processes are combined. The remaining settings are not important, but the combination can be set with attribute (“Rule” drop-down) or the attributes related to batch can be saved using different criterion through “Save Criterion” drop-down menu (Figure B.56).

The batch is followed by the removal of hazardous materials in the IHM from the ship by a specialised team. This can be yard personnel or an external company depending on the practice. Therefore, this step can change for every yard. Once the removal step is finished, quality check and authority check steps are conducted. Process modules are used in these steps while the quality check is conducted by the yard personnel (Seize Delay Release), Authority check is conducted by external (Delay). Data to collect from the yard and the resources involved in these operations are given in Table B.7.

Table B.7: Data to collect and resources involved in the preparation for recycle to step

Data to collect	**Resources involved**
IHM necessity percentage Duration of IHM Survey Assumptions if any will be made on the ship type, ship’s condition Duration of general cleaning Duration to discharge liquid waste The capacity of the crane The weight distribution of the ship and the amount of waste from the ship	Foreman Worker

B-3.4. Primary cutting and Removal of equipment and materials

Preparation for recycle step connects to two submodels; Primary cutting (and removal of equipment and materials), and Segregation and storage. This step will explain the approach in Primary cutting simulation model (Figure B.57).

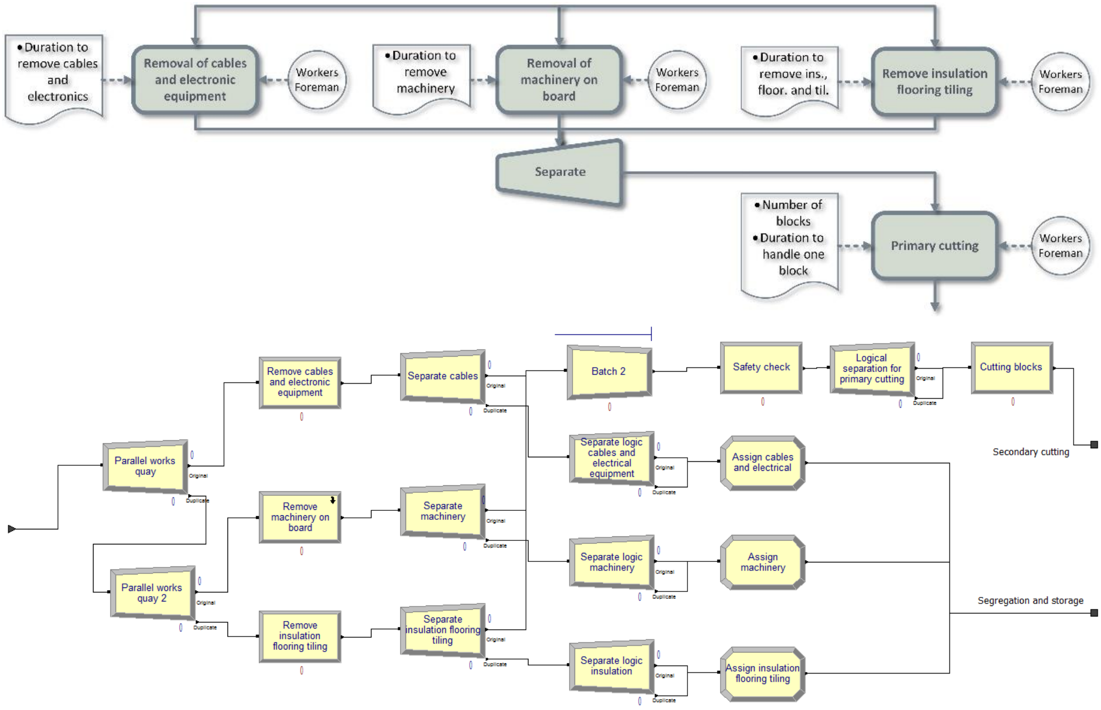


Figure B.57: Primary cutting step graphical representation (above) and translated to the Arena environment (below)

The process in the primary cutting zone starts with three parallel works; “Removal of cables and electronic equipment”, “Removal of machinery on board”, and “Removal of insulation, flooring and tiling”. Since these modules are parallel to each other, two separation modules are used and connected to create the three branch. For more branches, the same logic can be followed.

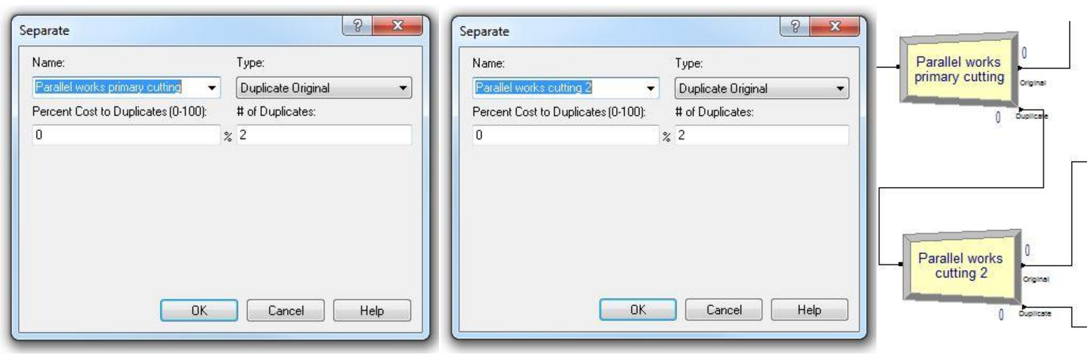


Figure B.58: Use of Separation for multiple branches (Separate logic on left and middle and connection on the right)

The machinery of the yard requires detailed approach to accurately represent the engine room dismantling.

On each branch, process modules are used to represent the removal of these materials from the ship. Similar to the previous section, Separate modules are used to divide the main entity and the waste as well as to accurately model the amount of material and equipment removed from the ship. Then Assign modules to allocate the "Material Index" attribute for separation step follow the separate logic.

After the separation, the Batch module used again to combine the three branches and Safety Check is conducted (Process with Delay logic). As a next step, blocks are removed from the ship to be further processed in the secondary cutting zone. At this point, there is only one entity progressing through the model. Therefore an assumption at this point is required to create duplicate entities, in other words, the blocks to be removed from the ship, is required. Similar to the creation of duplicates, the average carrying capacity of the crane can be used to calculate the number of blocks that will be cut from the ship. The example in Figure B.59 is calculated for the 11000 LDT ship in the thesis of Jain (2017) where the author provided the detailed material flow of the end-of-life ship. The assumption is made for a crane with maximum 15-ton capacity at 60 meters.

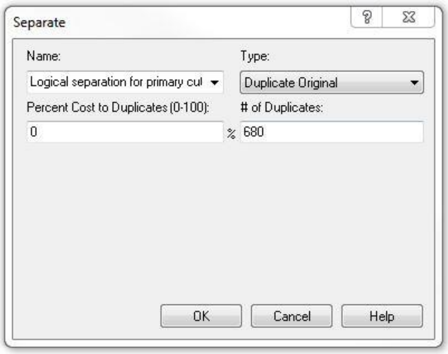


Figure B.59: Separation logic for the block dismantling in the Primary zone.

An alternative approach can be the calculation of block weights for different scenarios for different crane capacities (at different lengths) (Table B.8).

Table B.8: Alternative capacity and block numbers for the capacities

Capacity	**2.5**	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**22.5**	**25**	**27.5**	**30**
Blocks	4000	2000	1333	1000	800	667	571	500	444	400	364	333
Capacity	**32.5**	**35**	**37.5**	**40**	**42.5**	**45**	**47.5**	**50**	**52.5**	**55**	**57.5**	**60**
Blocks	308	286	267	250	235	222	211	200	190	182	174	167

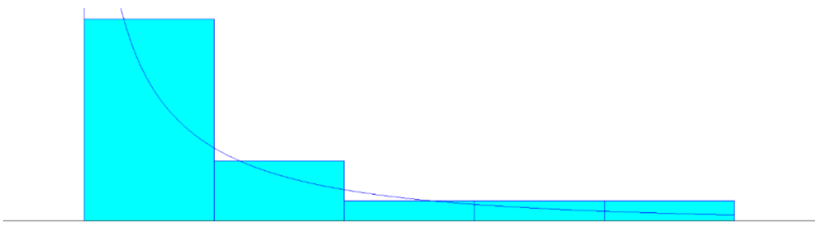


Figure B.60: Distribution of the block numbers

These capacities and block numbers can be analysed to find the best distribution and the equation as input using the Chi-Square test. Chi-Square test gives the following square errors and p-values for each distribution (Table B.9).

Table B.9: Analysis of the best distribution.

Function	**Sq Error**	**p-value**
Weibull	0.00127	< 0.005
Exponential	0.0123	< 0.005
Erlang	0.0123	< 0.005
Gamma	0.0228	< 0.005
Lognormal	0.0579	< 0.005
Beta	0.065	< 0.005

Normal	0.215	< 0.005
Triangular	0.275	< 0.005
Uniform	0.369	< 0.005

Table B.9 shows that the Weibull is the best distribution as the square error is minimum. However, it should be noted that even though the square error is minimum, p-value should also be checked (More detailed information on the square error, distribution and p-values were summarised in Section B-1 of this thesis). Separate module with WEIBULL distribution is shown in Figure B.61.

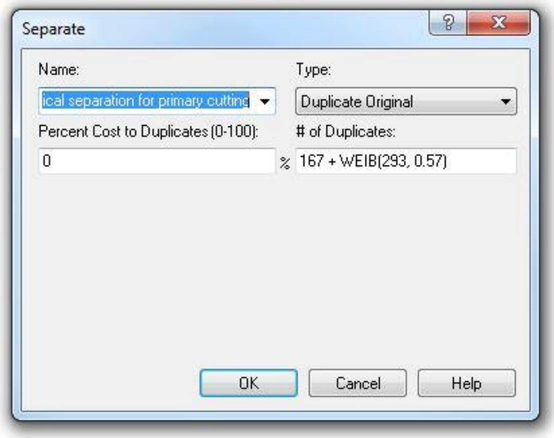


Figure B.61: Alternative Separation approach for duplicates

After the creation of blocks, the next step is the actual cutting of the blocks in the primary cutting zone (Figure B.62). A Process module is used to represent this step. A worker (sometimes with a helper) conducts this job, and one of the vital data collection studies belongs to this section. In this simulation model, the model is set in a way that only one type of block comes from the ship. Using an assign module different block types with different dismantling times can be defined for the simulation.

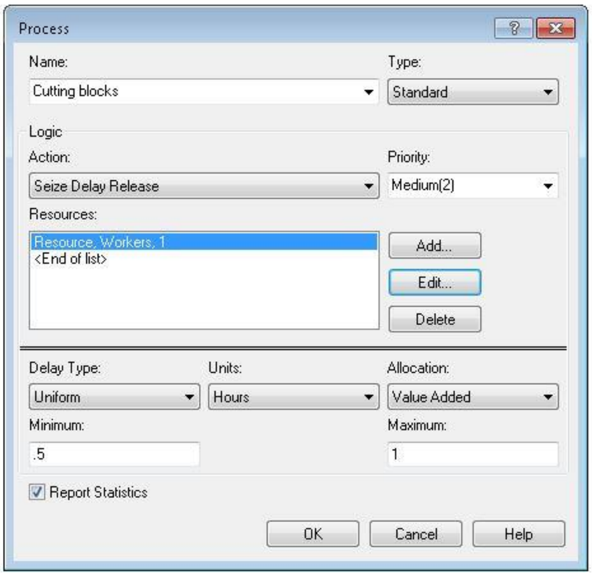


Figure B.62: Dismantling the ship to the blocks

The data to collect and resources involved in the primary cutting step of a ship is demonstrated in Table B.10

Table B.10: Data to collect and resources involved for the Primary cutting and Removal of equipment and materials

Data to collect	Resources involved
Amount of materials from the detailed material flow analysis The capacity of the crane Block dismantling time in the primary cutting zone Number of workers allocated for primary cutting zone The types of blocks in the ship (optional)	Workers Foreman

B-3.5. Further cutting in secondary cutting zone

The secondary cutting zone is one of the most activity-intensive zones in a ship recycling yard. Parts and blocks dismantled in the primary cutting zone sent to secondary cutting zone for further process. Primary cutting zone model ends with the cutting of the blocks from the ship. These blocks are transferred to the secondary cutting zone with a crane; transferred blocks are cut further in the secondary zone and transferred to relevant area (outside, segregation area, workshop or hazmat storage) (Figure B.63).

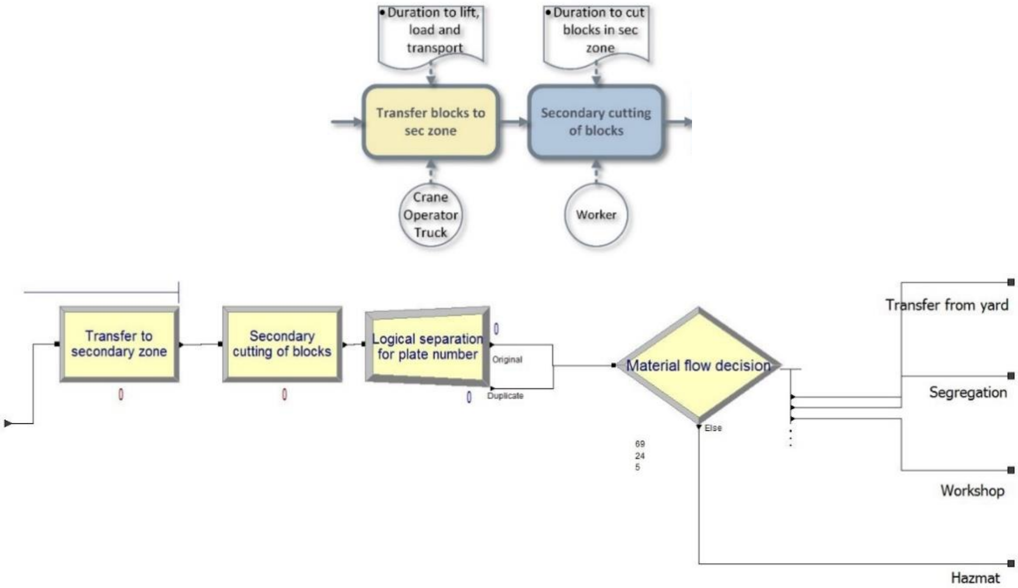


Figure B.63: Secondary cutting step graphical representation (above) and translated to the Arena environment (below)

Once the primary dismantling is finished in the primary cutting zone, blocks are transferred to the secondary cutting zone. This step is represented with a Process module (Figure B.64), but alternatively, transfer modules under the Advanced Transfer template of Arena can be used. The use of this template is demonstrated in Chapter 6 of this thesis. Attachment of the crane to the plate assumed to be included in this process, therefore, the expression shown in the (Figure B.64) Delay duration is the attachment to plate and transfer to the shore.

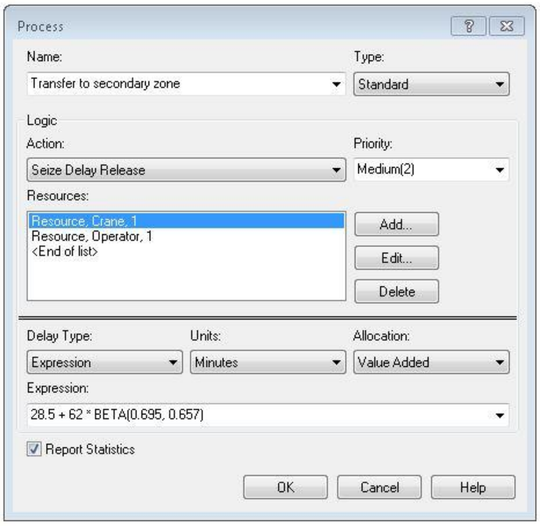


Figure B.64: Transfer to the secondary zone using Process module

Even though it was not included in this process flow, if the primary cutting zone and the secondary cutting zone is not adjacent hence additional transport is required, an additional step can be added for the transfer including the transferring resource and the duration for the transfer.

Once the block is transferred to secondary cutting zone, dismantling operation starts in the secondary zone. As mentioned in Chapter 7, the traditional approach is to use oxy-fuel (LPG, acetylene, propane commonly) torches and cut the plates to smaller pieces of which satisfies the requirement of the steel mill they will be sold to. This process is represented with a Process module shown in Figure B. 65.

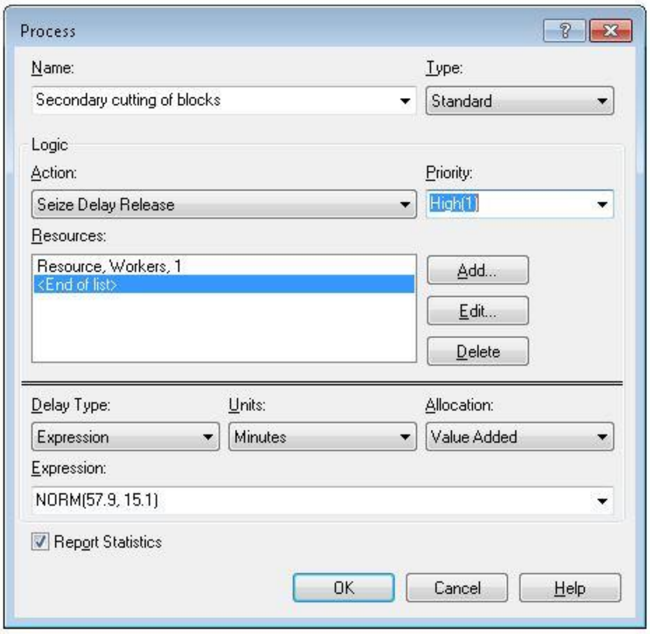


Figure B.65: Further dismantling in the secondary zone

Following the cutting of blocks, as mentioned before, smaller pieces of plates for transfer is acquired. In order to model the creation of smaller plates as entities (to accurately model the behaviour), the separate module is used again (Figure B.66).

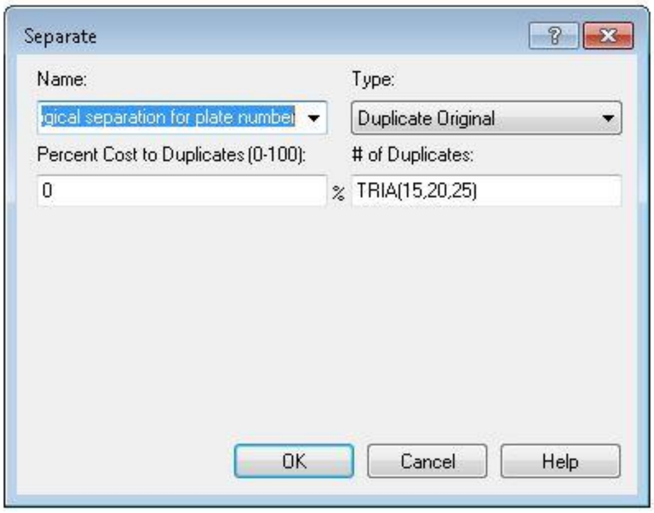


Figure B.66: Use of Separate module to represent the number of plates obtained after cutting

Following the separate module, decide module comes next to send the plates in the right process. The example in Figure B.67 uses N-way by chance (and percentages) to model this behaviour but instead Assign and Decide modules can be used together as an alternative approach. Decide module directs the entities towards Transfer from the yard, Segregation, workshop or hazmat storage according to the percentage chance.

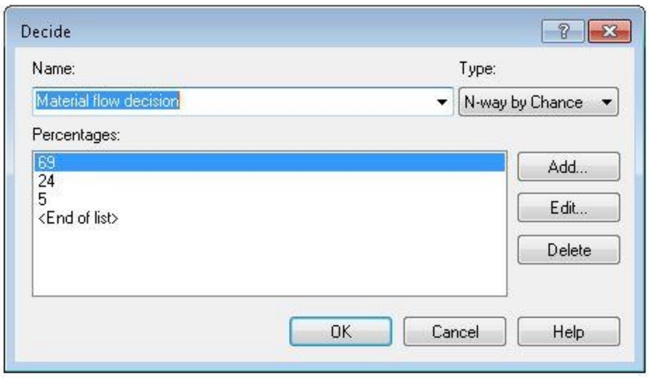


Figure B.67: Use of decide module with N-way by Chance logic

Secondary cutting zone simulation can seem straightforward, however, this is one of the most activity intense zones in ship recycling yard as mentioned before, therefore, accurate modelling of this zone is essential. Data collection for this zone will define the success of the simulation. Data to collect and the resources involved in this step is summarised in Table B.11.

Table B.11: Data to collect and resources involved in the Secondary cutting zone

Data to collect	**Resources involved**
Block transfer times with crane Block dismantling in secondary cutting zone Number of plates obtained from the blocks Transfer with	Crane Operator Worker Foreman (Truck depending on operation)

B-3.6. Segregation, Hazmat Treatment and Storage

Materials handled in Precleaning, Primary cutting zone and Secondary cutting zone are transferred to segregation zone for further treatment. The assumption in this submodel is that all the materials except the steel will be stored in the yard. In this submodel, transfer modules have not been used in order to simplify the modelling, but the implementation of transfer modules (from Arena's Advanced Transfer template) is demonstrated in Chapter 6 within the yard design case study.

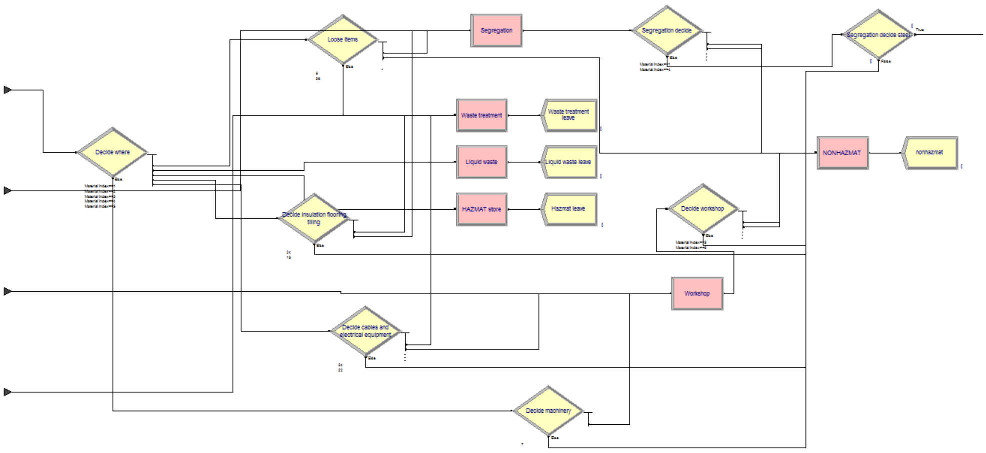


Figure B.68: Segregation, Hazmat Treatment and Storage step Arena representation)

The first module in this submodel is the Decide module which directs the entities according to the "Material Index" that was introduced previously.

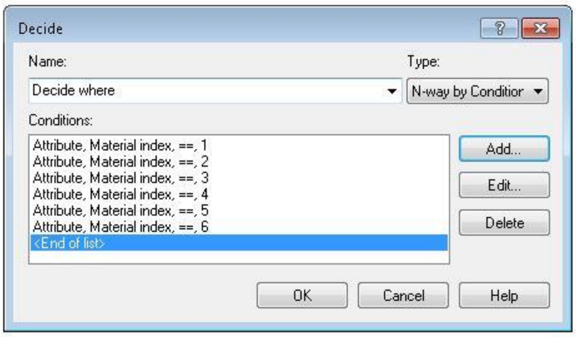
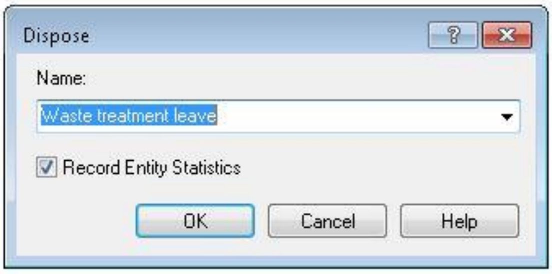


Figure B.69: Decide module directs the entities according to the material index

This section is entirely dependent on the analyst and the assumptions to be made. The full material flow of a case study ship should be studied to model this process accurately, or assumptions should be made on the experience on previous vessels. Decide module shown in Figure B.69 directs the entity to the relevant station and disposes of the entity (Figure B.70).



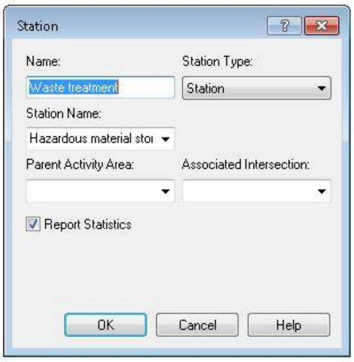


Figure B.70: Station and Dispose use within the submodel

The data that needs to be collected for this step has been summarised in Table B.12.

Table B.12: Data to collect and resources involved for the Segregation, Hazmat Treatment and Storage.

Data to collect	**Resources involved**
Material flow Assumptions on material quantities A decision on in yard transfer Process times for segregation, workshop and store if they will be included in the model	

B-3.7. Transport out of the yard

The last step of the simulation model is the transport of the steel out of the yard. The transport of the yard is only included in the model for steel acquired from the ship, but it can be expanded to other materials as well. The assumption as explained in the previous section was that all other materials would be stored in the yard for the simulation. The graphical representation and the Arena model of this step are shown in Figure B.71.

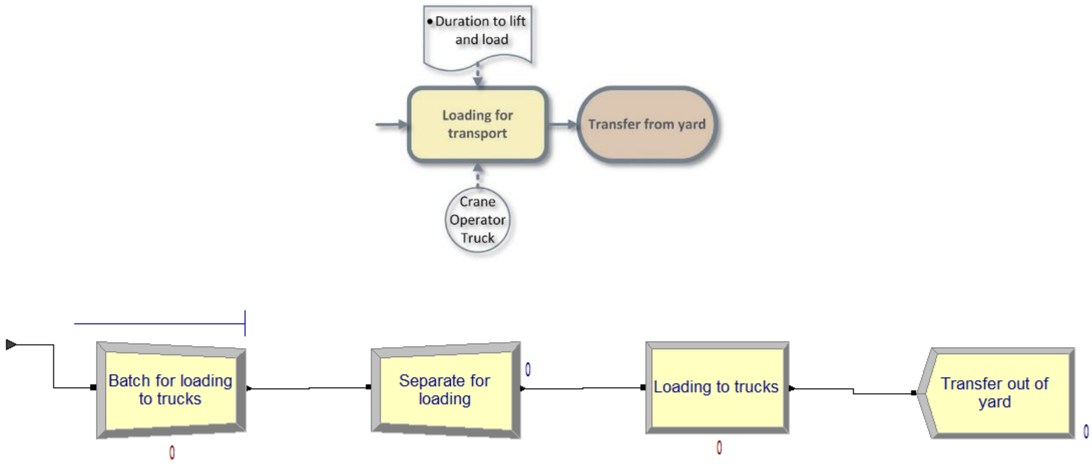
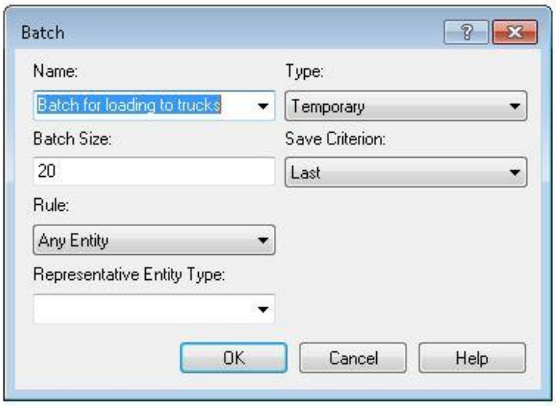


Figure B.71: Transport out of yard step graphical representation (above) and translated to the Arena environment (below)

The first module in the process is the Batch module (Figure B.72). The batch module is used in order to model the storing the panels cut in the Secondary cutting zone until they reach the truck's capacity. This logic is used in order to prevent an unrealistic scenario that might occur which is the loading of the panels as soon as they are cut from the block. Following the Batch, Separate (Figure B.72) is used to break the batched materials and accurately model the loading to trucks by the polygrab one by one.



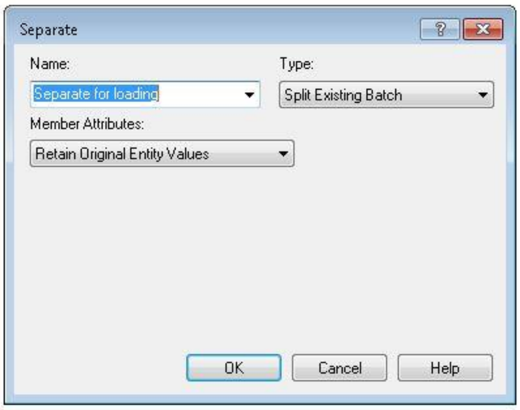


Figure B.72: Batch (left) and Separate (right) modules use to combine and split

After these two logical steps, loading to truck process is conducted using the Process module (Figure B.73).

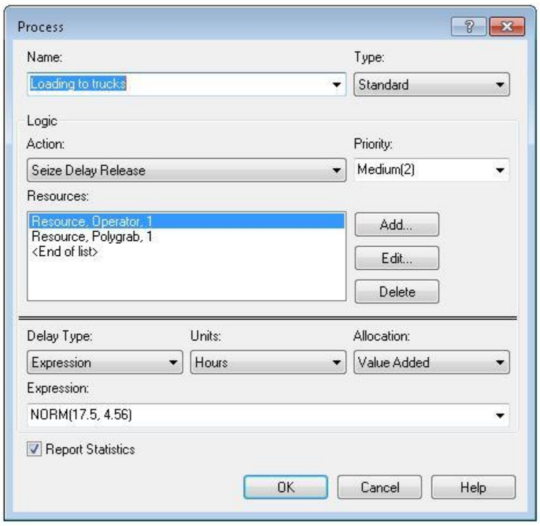


Figure B.73: Loading to trucks

After the loading, Dispose module represents the transfer out of the yard. If the yard is using its' resources to transfer these materials, an additional step can be added for transfer.

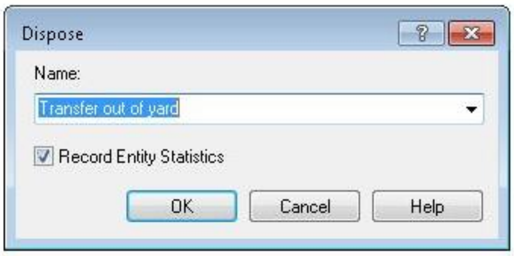


Figure B.74 Transfer out of the yard with dispose.

The data required for this step and the resources that should be included in the model are summarised in Table B.13.

Table B.13: Data to collect and resources involved for the Transport out of yard step

Data to collect	Resources involved
Truck capacities for a number of panels to load Number of panels loaded to trucks Duration to load the parts	Polygrab Operator Polygrab Truck

This section concludes the approach to overall model ship dismantling processes. Simulation model introduced in this section can be used to model the operations of an existing ship recycling yard to optimise the process, or it can be used in the (creation or modification of) design of a ship recycling yard.

B-4. Simulation Approach to Model the "Cutting Operations" in a Ship Recycling Yard

Ignoring all the docking, inspection, cleaning, waste treatment and equipment/machinery removal ship recycling procedure is all about cutting and dismantling of the steel structure of the ship. The steel obtained from the ship has different end-of-life options; higher quality steel plates that are heated and reused, sent to furnaces to be melted down, or in some cases panels are directly used if in very good condition. The overall process for the cutting is simplified in Figure B.75.

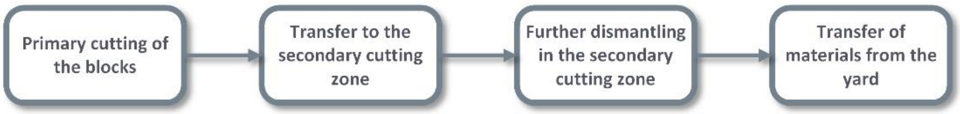


Figure B.75: Simplified cutting operation in yards.

There are two different cutting operations for steel in the yard; the first cutting operation is the dismantling of the blocks into the plates and other smaller pieces. The second is the primary cutting of the blocks; big blocks are removed from the ship according to the carrying capacity of the crane (or in beaching method the capacity of the winch as the typical approach is letting the block down using the gravity and pulling with winch).

As explained in Chapter 4, ship recycling yards prepare the steel according to the requirement of the steel mill. This operation can be easily modelled and simulated to test

- Different cutting sizes for plates,

  Every steel mill has different technical requirements for steel and different offer prices. Yards mainly consider the highest offer or the proximity even though the mill requires smaller piece than other mills. However, the difference in the size of the plates will affect the torch time (hence energy usage), worker time and emission.

- Implementation of different cutting technologies

  Oxy-fuel cutting is mainly used due to the very low investment cost, low training need and ease of operation. However, especially in the secondary cutting zone, performances of the cutters are very low. This is due to the low production rate of oxy-fuel cutting torches. Therefore, simulation can be used to investigate the use of alternative cutting methods and compare with the currently used oxy-fuel cutting method.

- Use of a different number of resource combinations

  Optimisation of resources is not conducted in the ship recycling industry commonly. Using the simulation approach, different resource combinations can be tested. A number of various worker numbers, in-yard transporters, crane capacities, Polygrab or operator numbers are one of the few examples that can be done.

In order to accurately model the cutting operation, several data collection studies in ship recycling yards were organised and cutting operations were observed.

In the secondary dismantling zone, worker (sometimes supported by a helper) cuts the transferred blocks from the primary cutting zone into smaller pieces. Overall, the worker follows a pattern similar to shown in Figure B.74. If the block or part consists of two pieces, the first worker separates these parts and then cuts the structural elements and panels to smaller pieces.

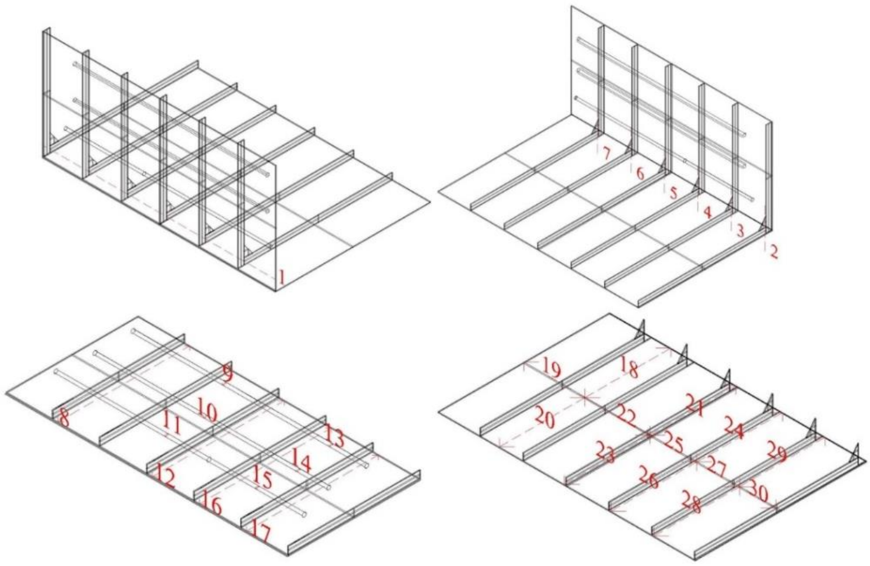


Figure B.76: Cutting lines for a block

Three different actions are involved during the cutting operation (assuming there is no interruption or breakdown or equipment);

1. Worker positions himself to cut the steel
2. Worker pre-heats the piece to be cut and pierces the steel
3. Worker conducts the cutting operation

This operation can be modelled in two different ways; case-based and randomness based.

B-4.1. Model for Case-Based Approach

Case-based modelling requires a selection of one or more case study block (as demonstrated in Chapter 7). Case study block should be investigated in detail, and cutting lines should be created similar to the example in Figure B.76. These cutting lines should be measured, and the cutting length should be recorded for each cutting line. The next step is the creation of the model.

The model should

- Create the blocks,
- Assign the required attributes and variables to entities,
- Conduct the positioning, heating and cutting operations,
- Dispose of cut parts.

The below model in Figure B.77 is designed for a single cutting line; each cutting line should be added to this model when modelling. Then the model needs to be ended with dispose module.

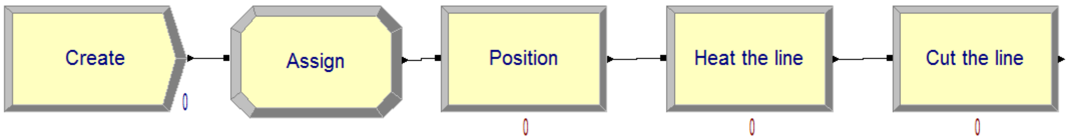


Figure B.77: Model for a single cutting line

However, since the process will be conducted by the same resource, an alternative approach can be done as shown in Figure B.78 to seize the resource once, repeatedly delay for each cutting line and release once, instead of seizing delaying and releasing for every position, heat the line and cut the line procedure. This will ease up the simulation process and will reduce the computer time.

Figure B.78: Alternative approach

Also, since positioning, heating and cutting share the same resource, these three steps can be combined and the time for each step can be reflected in one delay time.

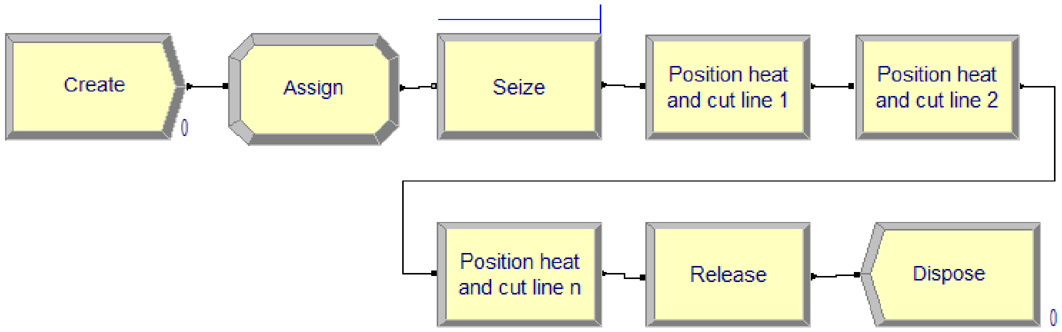


Figure B.79: More simplified simulation model

The critical step for this simulation is the collection of the data. As mentioned before, several data collection campaigns were conducted as part of this PhD study. During these data campaigns block dismantling operations were followed, and the below data were collected (The data collected for this step is shared within the Appendix D of this thesis):

- A worker positions himself to for the cut,
- Duration of Heating the piece through the cutting line and piercing,
- The length of the line and the duration for the cutting for the line.

During the data collection, it was observed that the worker's "positioning" and "heating and piercing" steps are often conducted together, therefore, the duration for this step is combined and a distribution that can be used as "Expression" when defining the process time is derived (Appendix D).

The critical step is the cutting of steel. Different approaches can be followed for this step. The first approach is the use of manufacturer data for cutting speed. Manufacturer data of the torch that can be used for the given thickness, if the cutting speed is multiplied with the cutting length duration of the operation can be found. Even though this method is easier, it has the risk of being inaccurate due to the involvement of human performance in the process. The cutting speeds in the manufacturer data sheet are given for optimum conditions. Therefore, the cutting speeds should be compared with the actual performance data of the worker.

Another approach for this is the recording of cutting speeds for different lengths. Using these record, cutting speed per minute can be found, and this can be extrapolated to an expression. In the case study in Chapter 7, both approaches are used, and both are compared with the actual cutting speed. A similar approach should be followed by the modeller. Also, the result of the simulation should be compared with the recorded data to verify and validate the model.

B-4.2. Random Model for Cutting

In this approach, a number of cutting lines in a block and cut line lengths are defined randomly by the distribution given by the modeller.

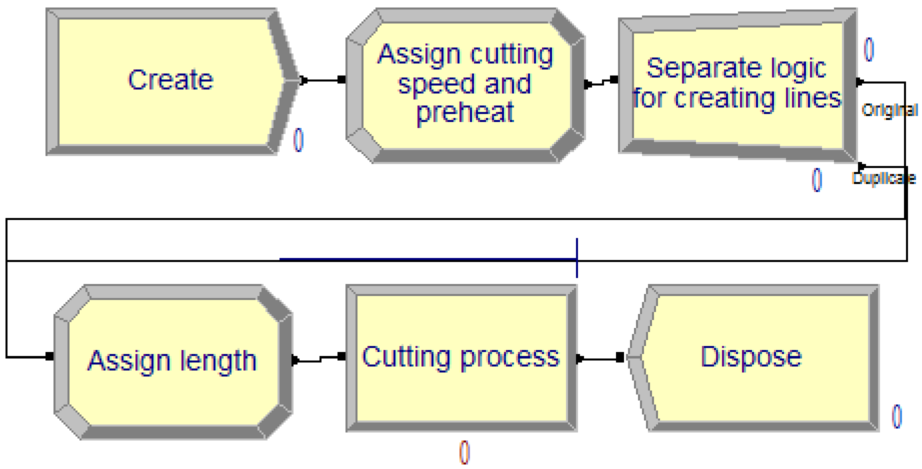


Figure B.80: Modelling of the cutting in the Secondary zone with Random Number generation.

Through the create module, the block is introduced to the system. First Assign module “Assign cutting speed” introduces the cutting speed of the torch to the simulation system while preheat duration introduces the Preheat duration obtained during the observation (equation shown is valid for 15 mm steel) (Figure B.81).

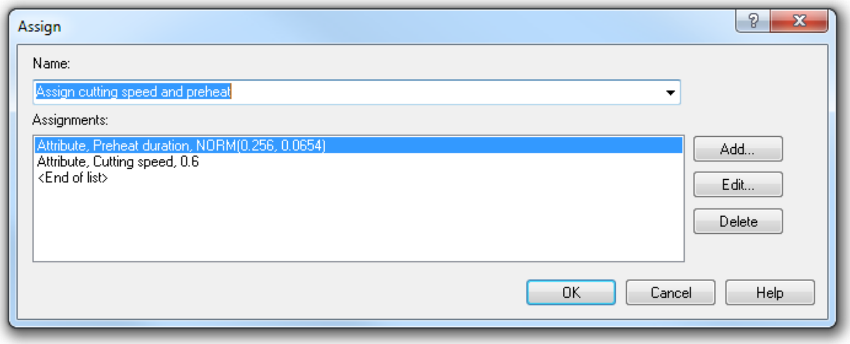


Figure B.81: Assign module for allocating the preheat duration and cutting speed

Next, entity goes through the separate module which creates the cutting lines with duplicate logic according to the number of lines defined by the modeller.

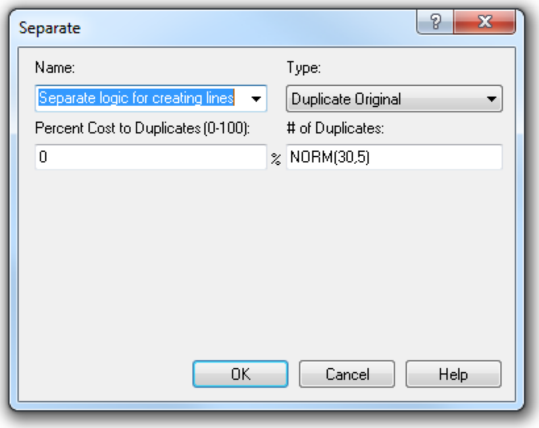


Figure B.82: Separate logic to create cutting lines

Following the separate module, Assign module is placed which randomly (according to the distribution given) assigns a cutting length to duplicated entities (Figure B.83). Cutting length shown here is obtained as a result of the data collection study in the yard (Appendix D).

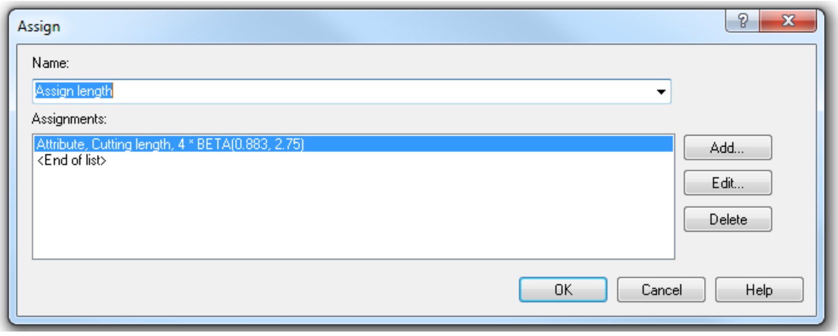


Figure B.83: Assign module for allocating cutting lengths

Once the cutting lengths are assigned, entities go through the Process module “Cutting process” where the cutting of the lines is represented. Delay time uses the attributes assigned previously in the model, which makes it easier to use the system for different technologies. Delay time equation divides the cutting length by the cutting speed (and finds the cutting time for the length) and adds the “reposition, preheat and pierce” duration for the given thickness (Figure B.84).

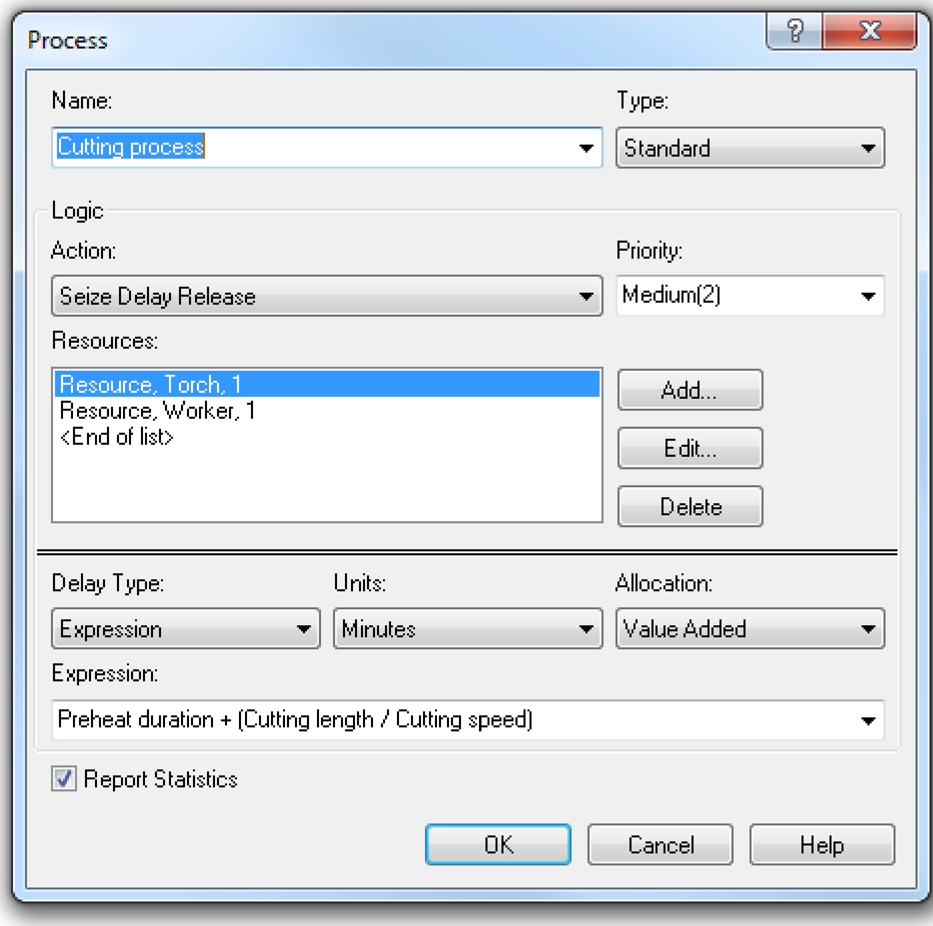


Figure B.84: Delay for the cutting process.

Once the process is finished, simulation disposes of the entities through the dispose module.

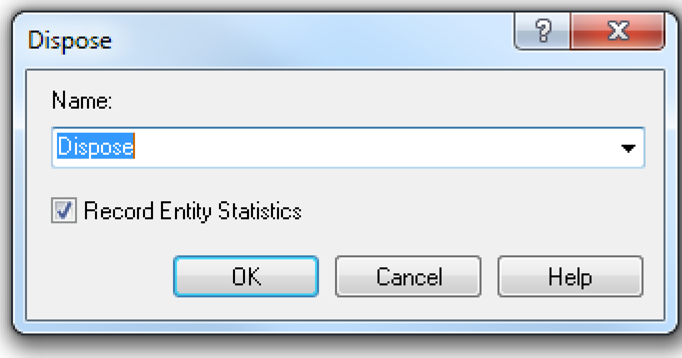


Figure B.85: Dispose

Ideally, this simulation should be run for an entire day to find out how many blocks can be dismantled or to find out the daily cost of operation, resource utilisation, queue times and so forth. The models shown in this section, 0, are validated and verified for several case studies. Model for case-based approach gives more sensitive result compared to randomness based approach. Therefore, Chapter 7 uses the case-based approach to test the different cutting technologies. However, randomness based approach is more suitable to the character of discrete event simulation as it is much more easier to apply, does not need specific calculation as required for case-based and the approach can be applied for the primary cutting zone as well. All is needed to investigate the cutting distances, a number of cutting lines per block and the cutting speed of the torch (and worker) used. The process in the primary zone can be modelled for different scenarios, simulated and optimised to find different methods, different resource combinations or costs for removing the blocks.

This section summarised the simulation approach for the cutting operation in ship recycling. Since the cutting operation is the most dominant activity in a ship recycling yard, a specific focus is given to this operation. Similar models can be generated for other operations in the yard.

Appendix C: Facility Layout Design Methodologies in the Literature

Effective factory layout planning is vital to the survival of manufacturers in a globally competitive environment (Prajapat et al., 2016) and an essential step in a facility's life cycle (Muther and Hales, 2015, Allegri, 1984)

The layout design of the facilities, which is commonly referred to as ''facility layout problem'', has a significant impact upon manufacturing costs, work in process, lead times and productivity (Drira et al., 2007). Well-designed facilities result in more efficient operations, decreased production times and reduced expenses up to 50% (Tompkins et al., 2010). On the other hand, a poor layout can be highly damaging to productivity (e.g. Lost time, idle equipment, and disruption of personnel) and consequently to profitability (Chabane, 2004). Chabane (2004) summarises the poor plan arrangement symptoms as;

- Providing for employees' safety, comfort and convenience,
- great travel distances in the material flow,
- bottlenecks in the resource shipment,
- excessive handling of materials,
- poor information circulation,
- inefficient communication system,
- the low rate of the machine and labour utilisation.

The leading cause of these problems can be summarised as the poor planning of the facilities, insufficient infrastructure of the facility, inefficient location arrangement of substations, poor handling equipment and inadequate processes and technology (Chabane, 2004). Therefore, the primary purpose of facility layout is to overcome these identified issues and to facilitate the effective manufacturing progress. Furthermore, facility layout planning also aims to address these following objectives (Muther and Hales, 2015);

- Efficient use of space
- Minimum material handling
- Maintaining flexibility for future needs
- Promoting high turnover of work-in-process

- Holding down investment in equipment
- Efficient use of resources

Ship recycling yards also have similar problems due to the planning with a traditional approach rather than a structured method. Therefore, a method for the design of ship recycling yards is required to overcome these issues and to increase the competitiveness of the ship recycling yards.

In literature, there are many different approaches to facility layout design. As also stated by Maina et al. (2018) some of these approaches are very advanced algorithmic methods (e.g. ant colony optimisation (Yu-Hsin Chen, 2013) or genetic algorithm technique (Gonçalves and Resende, 2015)). These methods are very sophisticated and require advanced knowledge of mathematical models (Chien, 2004). Considering the current level of the ship recycling industry, methods that are easier to apply should be considered. Procedural methods, which can link qualitative and quantitative factors (Apple, 1991) in the design process would be more appropriate for the ship recycling industry at this time. (e.g. Systematic Layout Planning of (Muther, 1973)).

In the literature, there are number advanced layout planning models (which are usually a set of procedures) that result in considerably efficient layouts (Maina et al., 2018). Some of the examples are

- Immer's Approach (1950)
- Nadler's Ideal System Approach (1961)
- Apple's 20 step method (1977)
- Reed's 10 step method for layout method (1961),
- Muther's systematic layout planning method (1961).

In addition to these methods listed above, more recent approaches such as heuristic algorithms (Urban, 1993), dynamic layout algorithms (Balakrishnan et al., 2000), ant colony optimisation (Baykasoglu et al., 2006), were also investigated. However, considering the nature of the ship recycling industry, more simplistic approach was required. Therefore, these advanced methods were not investigated further.

Immer's Layout Design Approach

Immer's approach consists of three steps; put the problem on paper, show lines of flow, and convert flow lines to machine lines. Immer's approach works best with existing layout with a need for improvement or change, but it is not very useful when it comes to new facilities (Grassie, 2009).

Ideal System Approach of Nadler

The initial aim for the Nadler's ideal system approach was to design work systems, but the approach is also very relevant to facility design. Nadler's approach follows these four steps (Tompkins et al., 2010);

1. Aim for the "theoretical ideal system."
2. Conceptualise the "ultimate ideal system."
3. Design the "technologically workable ideal system."
4. Install the "recommended system.

Apple's 20 step method

Apple developed a sequence of 20 steps, and these steps do not necessarily have to be performed in the order that it is given. The steps are (Apple, 1991);

1. Procure the basic data,
2. Analyse the basic data,
3. Design the productive process,
4. Plan the material flow pattern,
5. Consider the general material handling plan,
6. Calculate equipment requirements,
7. Plan individual workstations,
8. Select specific material handling equipment,
9. Coordinate groups of related operations,
10. Design activity interrelationships,
11. Determine the storage requirements,
12. Plan service and auxiliary activities,
13. Determine space requirements,
14. Allocate activities to total space,
15. Consider building types,

16. Construct a master layout,
17. Evaluate, adjust and check the layout with the appropriate persons,
18. Obtain approvals,
19. Install the layout,
20. Follow up on the implementation of the layout.

Reed's Plant Layout

Reed developed the "systematic plan of attack", for the planning and preparation of a facility's layout (Tompkins et al., 2010). Steps in this "plan of attack" are (Reed, 1961):

1. Analyse the product or products to be produced,
2. Determine the process required to manufacture the product,
3. Prepare layout planning charts. (which is the most crucial step of the method according to Reed (Reed, 1961)),
4. Determine workstations,
5. Analyse storage area requirements,
6. Establish minimum aisle widths,
7. Establish office requirements,
8. Consider personnel facilities and services,
9. Survey plant services,
10. Provide for future expansion.

Muther's systematic layout planning (SLP)

As Kulkarni et al. (2015) reported Muther's SLP is still widely used for layout design even though it is a traditional approach, and is derived way back in 1961. According to the (Muther, 1973), there are two elements related to the layout problem

- Product (or material or service) – what is to be made or produced
- Quantity (or volume) – how much of each item is to be made

Obtaining the information on these two elements are the first step of solving the problem as they directly or indirectly affect the whole process. After product and quantity are identified routing (process sequence), supporting services and time should be identified (Muther and Hales, 2015).

Muther and Hales (2015) explain the (Systematic) Layout Planning as "*an organised way to conduct layout planning which consists of a framework of phases, a pattern of procedures, and a set of conventions for identifying, rating and visualising the elements and areas involved in planning a layout"*. The phases of the layout planning according to the Muther are summarised in Table C.1.

Table C.1: Phases of layout plans and descriptions according to (Muther and Hales, 2015)

Phase	Description
Phase I – Location	Determine the location of the area to be laid out.
Phase II – General Overall Layout	Establish the general arrangement of the area to be laid out.
Phase III – Detailed layout Plans	Locate each specific piece of machinery and equipment.
Phase IV – Installation	Plan the installation, seek the approval of the plan, and make the necessary physical moves.

Three fundamentals should be studied for the successful layout; relationships between the elements, space (actual and needed), and adjustment which is the optimisation for the best fit (Muther and Hales, 2015). These fundamentals are the main focus of the Muther's Systematic Layout Planning (SLP) pattern which consists of five sections (Muther and Hales, 2015).

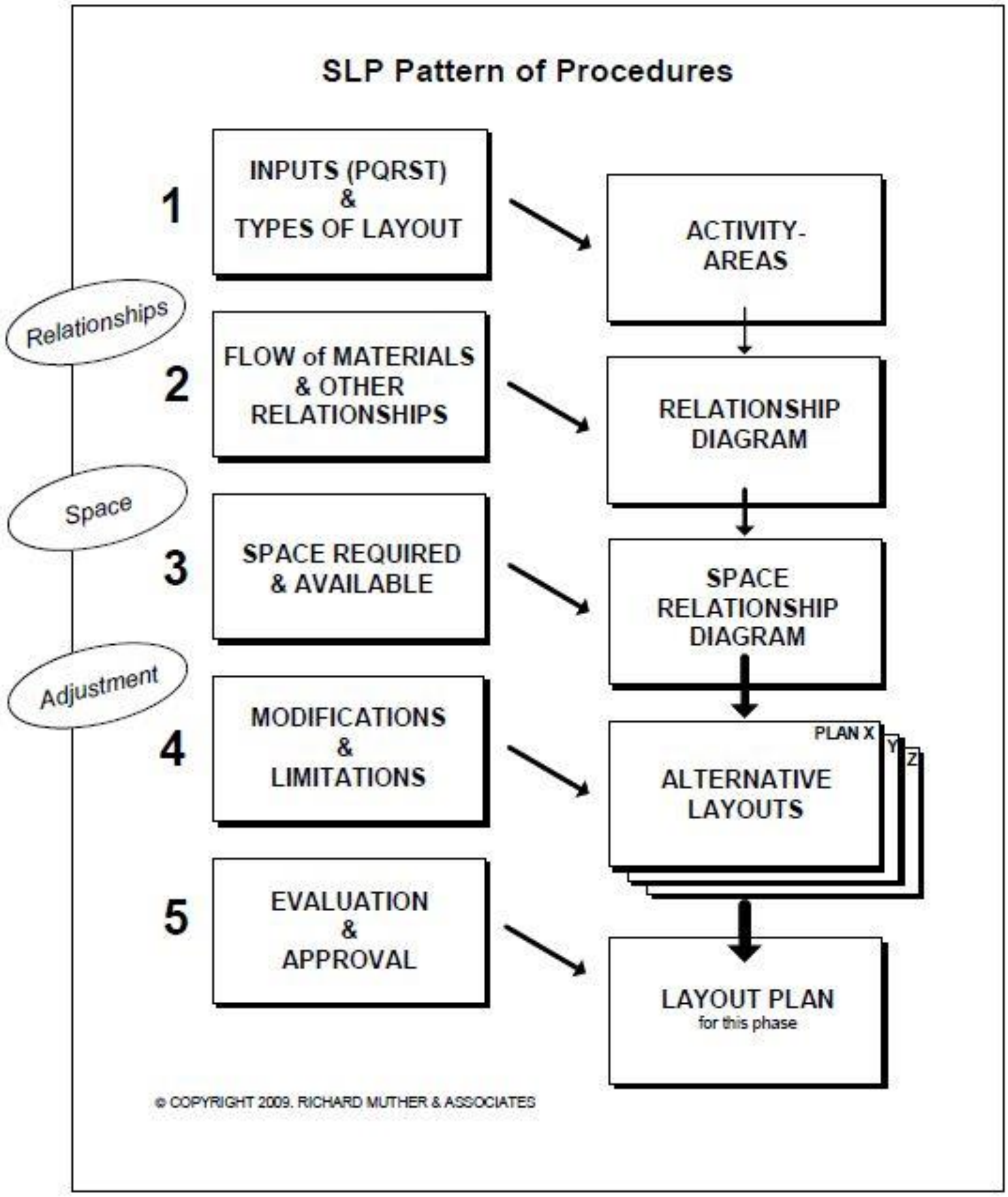


Figure C.1: Systematic Layout Planning Pattern (Muther and Hales, 2015)

The first step of the framework of Muther is the analysis of inputs (P, Q, R, S and T which is introduced in this section) which outputs a list of Activity-Areas (e.g. departments, product value streams, docks and entrances). The second step is determining the material flow and the relationships between the units/departments/elements. The output, flow and relationship analysis, is combined with the activity areas from the previous step to form the relationship diagram. The next step, available and required space for the activities, machinery and departments are analysed and checked with available space. The area allowed for activities combined with the relationship diagram and space relationship diagram is formed. This diagram is basically a layout and this is modified to the alternative layouts in step 4. The final step is the evaluation and approval of these layouts to decide on the layout plan for the phase. In Phase II general overall layout is developed and in phase III detailed layout plans of each area, which have been developed roughly in phase II, are developed (detailed layout plan must be made for each of the departmental areas involved). Same steps for both phases can be used.

In some cases, there may not be a need for four phases depending on the size of the project. For these types of projects, a short-form, six-step procedure called *Simplified Systematic Layout Planning* can be used. Simplified SLP condenses the phases, levels and tasks of the full methodology into the following steps:

1. Chart the relationships
2. Establish space requirements
3. Develop the activity relationships diagram
4. Draw space relationship layouts
5. Evaluate alternative arrangements
6. Detail the selected layout plan

Muther's method is commonly accepted and applied methodology for designing and improving the facility layouts (Song and Woo, 2013, Maina et al., 2018). This method is very promising and with adaptations, it can be applied to ship recycling yard development.

Appendix D: Data Collection and Distributions

D1. Generic Data

<u>D1.1 Access to Ship</u>

Number	Time (min)	Number	Time (min)
1	01:30	6	02:15
2	02:30	7	01:49
3	02:30	8	01:35
4	02:00	9	02:05
5	02:00	10	02:28

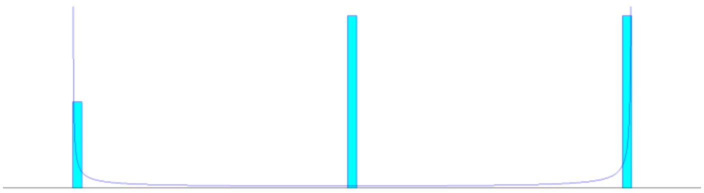
<u>Distribution Summary</u>

Distribution: Beta
Expression: 89.5 + 61 * BETA(0.251, 0.168)
Square Error: 0.205535

<u>Data Summary</u>

Number of Data Points = 10
Min Data Value = 90
Max Data Value = 150
Sample Mean = 126
Sample Std Dev = 25.1

<u>Histogram Summary</u>



Histogram Range = 89.5 to 151
Number of Intervals = 61

<u>D1.2 Crane Operations</u>

<u>D1.2.1 Setup for Loading</u>

Number	Time (min)	Time (seconds)
1	02:00	120.00
2	01:46	106.00
3	01:36	96.00
4	02:00	120.00
5	02:15	135.00

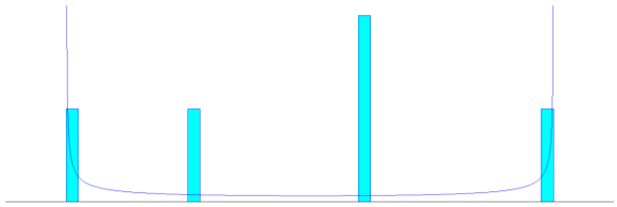
Distribution Summary

Distribution: Beta
Expression: 95.5 + 40 * BETA(0.396, 0.4)
Square Error: 0.207948

Data Summary

Number of Data Points: 5
Min Data Value: 96
Max Data Value: 135
Sample Mean: 115
Sample Std Dev: 14.9

Histogram Summary



Histogram Range = 95.5 to 136
Number of Intervals = 40

D1.2.2 Transfer to shore

Number	Time (min)	Time (seconds)	Number	Time	Time
1	01:00	60	7	00:59	59
2	01:30	90	8	01:15	75
3	00:29	29	9	01:27	87
4	01:21	81	10	00:48	48
5	00:43	43	11	00:45	45
6	00:47	47			

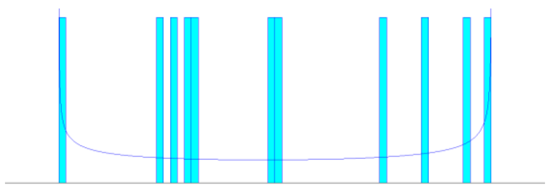
Distribution Summary

Distribution: Beta
Expression: 28.5 + 62 * BETA(0.695, 0.657)
Square Error: 0.069387

Data Summary

Number of Data Points: 11
Min Data Value: 29
Max Data Value: 90
Sample Mean: 60.4
Sample Std Dev: 20.2

Histogram Summary



Histogram Range: 28.5 to 90.5
Number of Intervals: 62

D1.2.3 Rotate and Load on Truck

Number	Time (min)	Time (seconds)
1	01:00	60
2	01:30	90
3	00:29	29
4	01:21	81
5	00:43	43

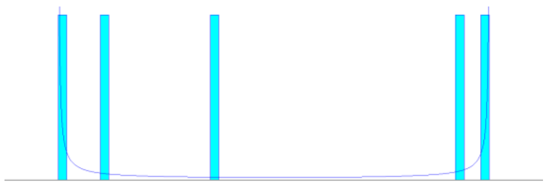
Distribution Summary

Distribution: Beta
Expression: 39.5 + 51 * BETA(0.0924, 0.1)
Square Error: 0.115707

Data Summary

Number of Data Points = 5
Min Data Value = 40
Max Data Value = 90
Sample Mean = 64
Sample Std Dev = 23.3

Histogram Summary



Histogram Range = 39.5 to 90.5

Number of Intervals = 51

D1.2.4 Primary Cutting

No	Time (min)	Time sec	No	Time (min)	Time sec
1	25.55	1532.754	6	21.93	1315.542
2	20.59	1235.256	7	51.49	3089.4
3	26.10	1565.772	8	21.31	1278.774
4	29.33	1759.62	9	36.38	2182.56
5	29.19	1751.67			

Distribution Summary

Distribution: Uniform

Expression: UNIF(20, 46)

Square Error: 0.133333

Kolmogorov-Smirnov Test

Test Statistic = 0.419

Corresponding p-value = 0.0631

Data Summary

Number of Data Points = 9

Min Data Value = 20.6

Max Data Value = 45.5

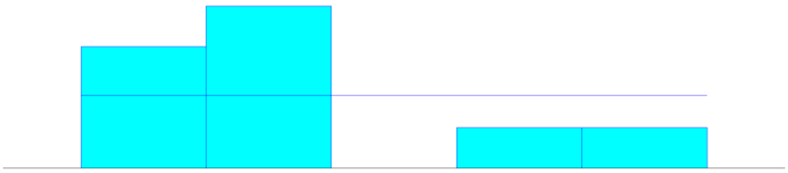
Sample Mean = 28.4

Sample Std Dev = 8.09

Histogram Summary

Histogram Range = 20 to 50

Number of Intervals = 5



D1.3 Secondary Cutting Zone

Number	Time (min)	Time sec	Number	Time (min)	Time sec
1	57.04	3422.526	19	65.7622	3945.732
2	63.07	3784.026	20	52.3969	3143.814
3	54.79	3287.454	21	64.0467	3842.802
4	50.03	3001.572	22	50.5454	3032.724
5	71.13	4267.686	23	54.8419	3290.514
6	57.64	3458.244	24	69.8415	4190.49
7	56.39	3383.586	25	41.7954	2507.724
8	66.48	3988.686	26	65.0108	3900.648
9	65.61	3936.702	27	68.5327	4111.962
10	65.03	3901.656	28	57.2258	3433.548
11	57.91	3474.504	29	69.7489	4184.934
12	65.27	3916.188	30	54.9733	3298.398
13	61.29	3677.604	31	52.0302	3121.812
14	53.75	3225.114	32	60.554	3633.24
15	45.83	2749.542	33	62.6995	3761.97
16	43.30	2598.024	34	70.9276	4255.656
17	68.5051	4110.306	35	67.6217	4057.302
18	47.6788	2860.728	36	75.4726	4528.356

Distribution Summary

Distribution: Triangular

Expression: TRIA(41, 67.3, 76)

Square Error: 0.022462

Chi Square Test

Number of intervals = 4

Degrees of freedom = 2

Test Statistic = 4.2

Corresponding p-value = 0.133

Kolmogorov-Smirnov Test

Test Statistic = 0.161

Corresponding p-value 0.15

Data Summary

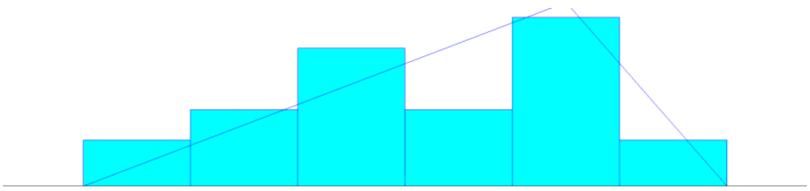
Number of Data Points = 36

Min Data Value = 41.8

Max Data Value = 80.5

Sample Mean = 59.9

Sample Std Dev = 8.5



D1.3.1 Profile

D1.3.1.1 Preheat and Pierce (Oxyfuel)

Number	Time (min)	Time (seconds)
1	00:12	12
2	00:14	14
3	00:10	10
4	00:09	9
5	00:12	12
6	00:16	16

Distribution Summary

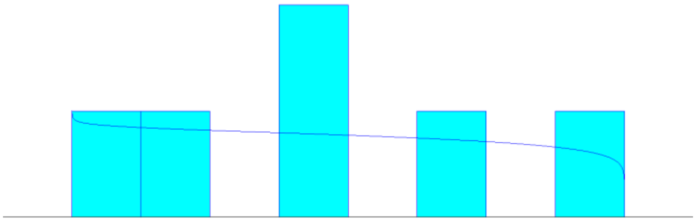
Distribution: Beta
Expression: 8.5 + 8 * BETA(0.978, 1.1)
Square Error: 0.096172

Data Summary

Number of Data Points = 6

Min Data Value = 9
Max Data Value = 16
Sample Mean = 12.2
Sample Std Dev = 2.56

Histogram Summary



Histogram Range = 8.5 to 16.5
Number of Intervals = 8

D1.3.2 Plate

D1.3.2.1 Preheat and Pierce (Oxyfuel)

Number	Time (min)	Time (seconds)	Number	Time (min)	Time (seconds)
1	00:12	12	**10**	00:20	20
2	00:14	14	**11**	00:15	15
3	00:10	10	**12**	00:20	20
4	00:09	9	**13**	00:19	19
5	00:12	12	**14**	00:17	17
6	00:16	16	**15**	00:20	20
7	00:20	20	**16**	00:15	15
8	00:09	9	**17**	00:17	17
9	00:11	11	**18**	00:24	24

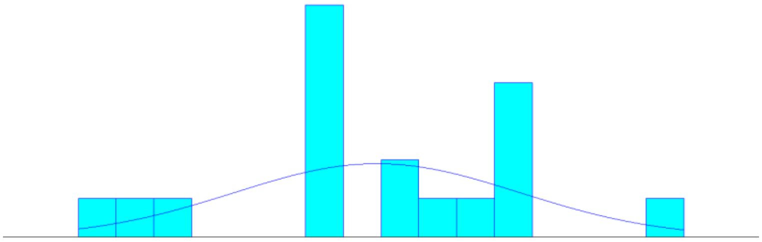
Distribution Summary

Distribution: Normal
Expression: NORM (16.4, 3.77)
Square Error: 0.116871

Data Summary

Number of Data Points: 18
Min Data Value: 9
Max Data Value: 24
Sample Mean: 16.4
Sample Std Dev: 3.88

Histogram Summary



Histogram Range: 8.5 to 24.5
Number of Intervals: 16

D1.3.3 Profile and Plate combined

D1.3.3.1 Preheat and Pierce (Oxyfuel)

Number	Time (min)	Time (seconds)	Number	Time (min)	Time (seconds)
1	00:20	20	**13**	00:15	15
2	00:09	9	**14**	00:15	15
3	00:11	11	**15**	00:15	15
4	00:20	20	**16**	00:15	15
5	00:15	15	**17**	00:10	10
6	00:20	20	**18**	00:18	18
7	00:19	19	**19**	00:12	12
8	00:17	17	**20**	00:14	14
9	00:20	20	**21**	00:10	10
10	00:15	15	**22**	00:09	9
11	00:17	17	**23**	00:12	12
12	00:24	24	**24**	00:16	16

Distribution Summary

Distribution: Poisson
Expression: POIS(15.3) (seconds) , NORM(0.256, 0.0654) (minutes)
Square Error: 0.058180

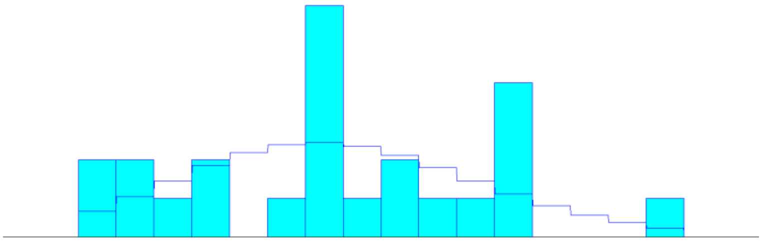
Chi Square Test

Number of intervals = 3
Degrees of freedom = 1
Test Statistic = 1.14
Corresponding p-value = 0.302

Data Summary

Number of Data Points = 24
Min Data Value = 9
Max Data Value = 24
Sample Mean = 15.3
Sample Std Dev = 4.01

Histogram Summary



Histogram Range = 8.5 to 24.5
Number of Intervals = 16

1.3.3.2 Cutting Data of Worker (Oxyfuel)

DISTANCE	TOTAL DURATION	M/MIN	Preheat+Pierce	Cutting	M/MIN
3.75	07:30	0.5	00:20	07:10	0.523256
1.75	02:53	0.606936	00:09	02:44	0.640244
1.75	02:53	0.606936	00:11	02:42	0.648148
1.75	02:55	0.6	00:20	02:28	0.677419
1.75	02:54	0.603448	00:15	02:24	0.660377
1.25	02:26	0.513699	00:20	02:06	0.595238
1	01:54	0.526316	00:19	01:32	0.631579
1.25	02:05	0.535714	00:17	01:48	0.609756
1.25	02:25	0.517241	00:20	02:05	0.6
1.03	01:58	0.523729	00:15	01:43	0.6
1.25	02:07	0.547445	00:17	01:50	0.625
1.25	03:00	0.416667	00:24	02:36	0.480769
0.82	01:31	0.540659	00:15	01:16	0.647368
1.25	02:26	0.510204	00:15	02:11	0.568182
0.72	01:20	0.48	00:15	01:05	0.576
1.25	02:28	0.506757	00:15	02:13	0.56391
1.25	02:30	0.5	00:10	02:20	0.535714
0.72	01:35	0.454737	00:18	01:17	0.561039

D1.3.3.3 Cutting Data for Torch (Oxyfuel)

Metal Thickness	Pressure kg/cm2		Consumption Nl/hr			Cutting speed
mm	oxygen	fuel gas	cutting oxygen	preheat oxygen	fuel gas	mm/min
5	7.0	0.2	750	1180	310	750
5-10	7.0	0.2	1100	1180	310	750-680
10-15	7.0	0.2	2500	1180	310	680-600
15-30	7.0	0.25	3800	1370	360	600-500
30-40	7.0	0.25	5400	1370	360	500-450
40-50	7.0	0.3	7300	1860	490	450-400

D1.3.4 Fittings

D1.3.4.1 Preheat and Pierce

Number	Time (min)	Time (seconds)
1	00:09	9
2	00:05	5
3	00:15	15
4	00:09	9
5	00:10	10
6	00:08	8
7	00:10	10
8	00:09	9
9	00:10	10

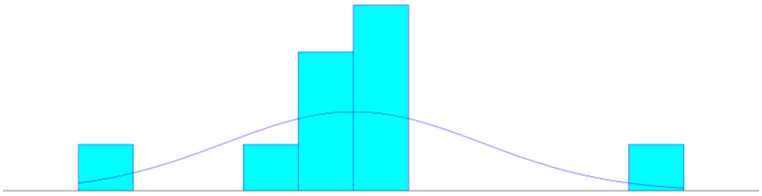
10	00:10	10

Distribution Summary

Distribution: Normal
Expression: **NORM(9.5, 2.33)**
Square Error: 0.132319

Data Summary

Number of Data Points = 10
Min Data Value = 5
Max Data Value = 15
Sample Mean = 9.5
Sample Std Dev = 2.46



Histogram Summary

Histogram Range = 4.5 to 15.5
Number of Intervals = 11

D1.3.5 Repositioning

Number	Time (min)	Time (seconds)	Number	Time (min)	Time (seconds)
1	00:45	45	**15**	00:04	4
2	00:14	14	**16**	00:02	2
3	00:06	6	**17**	00:08	8
4	00:07	7	**18**	00:09	9
5	00:09	9	**19**	00:04	4
6	00:02	2	**20**	00:27	27
7	00:02	2	**21**	00:44	44
8	00:04	4	**22**	00:05	5
9	00:08	8	**23**	00:23	23
10	00:04	4	**24**	00:26	26
11	00:06	6	**25**	00:02	2
12	00:27	27	**26**	00:15	15
13	00:02	2	**27**	00:02	2
14	00:08	8	**28**	00:10	10

Distribution Summary

Distribution: Beta
Expression: 1.5 + 44 * BETA(0.478, 1.19)
Square Error: 0.035844

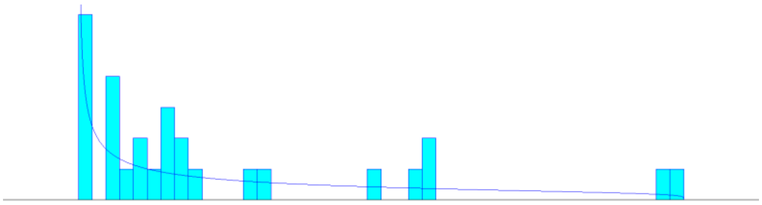
Chi Square Test

Number of intervals = 4

Degrees of freedom = 1
Test Statistic = 7.03
Corresponding p-value = 0.0084

Data Summary

Number of Data Points = 28
Min Data Value = 2
Max Data Value = 45
Sample Mean = 11.6
Sample Std Dev = 12.1



Histogram Summary

Histogram Range: 1.5 to 45.5
Number of Intervals: 44

D1.4 Loading to Truck with Polygrab

Number	Time (min)	Time (seconds)	Number	Time (min)	Time (seconds)
1	00:15	15	13	00:20	20
2	00:10	10	14	00:20	20
3	00:11	11	15	00:18	18
4	00:16	16	16	00:21	21
5	00:19	19	17	00:22	22
6	00:19	19	18	00:25	25
7	00:08	8	19	00:17	17
8	00:15	15	20	00:20	20
9	00:14	14	21	00:21	21
10	00:15	15	22	00:25	25
11	00:15	15	23	00:25	25
12	00:16	16	24	00:12	12

Distribution Summary

Distribution: Normal
Expression: NORM(17.5, 4.56)
Square Error: 0.033843

Chi Square Test

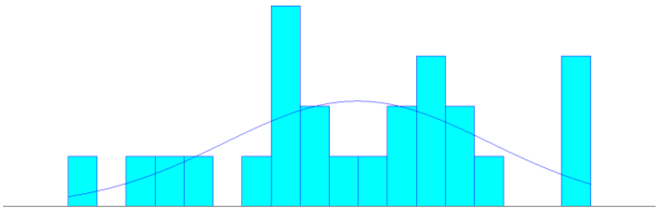
Number of intervals = 4
Degrees of freedom = 1
Test Statistic = 0.484
Corresponding p-value = 0.492

Data Summary

Number of Data Points = 24
Min Data Value = 8
Max Data Value = 25
Sample Mean = 17.5

Sample Std Dev = 4.65

Histogram Summary



Histogram Range = 7.5 to 25.5

Number of Intervals = 18

D1.5 Interview Data

D1.5.1. Engine room dismantling

The information you provide in this survey will be used for research purposes and your personal information will be kept confidential. The main aim of this research is to conduct simulation study for dismantling of the engine room in an end of life ship

Which one of the following options describes you best? Please specify.

Academic Staff ____________________

Seaman (Engineer) ____________________

Seaman (Rating) ____________________

Shipyard Worker ____________________

Student (have a seagoing experience) ____________________

Student (have no seagoing experiences) ____________________

What is your education level?

High School

University or Degree

Master Degree

PhD

Student (still studying)

Others ____________________

How many years do you have an experience on ships

Less than a year

1 to 3 years

3 to 5 years

5 to 10 years

More than 10 Years

No experience

Please fill the questions on below,

	Very Good	Good	Neutral	Poor	Very Poor
Q1. How do you rate your knowledge about ships?					
Q2. How do you rate your knowledge about Ship Engine Room?					
Q3. How do you rate your knowledge about Recycling?					
Q4. How do you rate your knowledge on End of Life Materials?					
Q5. How do you rate your knowledge on ship dismantling?					

Q6. How long does Funnel dismantling take?

Man hours ____________________

I do not know.

Q7. How long does exhaust gas boiler dismantling (flange to flange, all part together) take?

Man hours ____________________

I do not know.

Q8. How long does boilers and its pumps dismantling (all unit) take?

Man hours ____________________
I do not know.

Q9. How long does all exhaust line and its isolation, expansion joints dismantling take?
Man hours ____________________
I do not know.

Q10. How long does all boiler control unit(panels) dismantling take?
Man hours ____________________
I do not know.

Q11. How long does whole diesel engine/generator dismantling (500kW – 750kW) take?
Man hours ____________________
I do not know.

Q12. How long does diesel generators' control panels dismantling take?
Man hours ____________________
I do not know

Q13. How long does separator and its control unit/equipment (all stuff and whole system dismantling on foundation) dismantling take?
Man hours ____________________
I do not know.

Q14. How long does the typical booster unit on board ship (all equipment/unit) dismantling take?
Man hours ____________________
I do not know.

Q15. How long does fuel pumps (transfer, supply/feed) dismantling take?
Man hours ____________________
I do not know.

Q16. How long does heat exchanger (L/O, F/W) dismantling take? (assume that those of them has same dimensions)
Man hours ____________________
I do not know.

Q17. How long does Fresh Water Generator (including ejector pump) dismantling take?
Man hours ____________________
I do not know.

Q18. How long does all fresh water pumps (for cooling) dismantling take?
Man hours ____________________
I do not know.

Q19. How long does steering gear and control unit (emergency equipment's are included) dismantling take?
Man hours ____________________
I do not know.

Q20. How long does reduction gear (whole, from the connection points) dismantling take?
Man hours ____________________
I do not know.

Q21. How long does shaft generator dismantling take?
Man hours ____________________
I do not know.

Q22. How long does typical 4 stroke main engine (whole engine, up to 10.000 kW) dismantling take?
From foundations, whole (Man hours) ____________________
By disassembling (Man hours) ____________________
I do not know.

Q23. How long does main and service air compressor dismantling take?
Main Air Compressor (Man hours) ____________________
Service Air Compressor (Man hours) ____________________
I do not know.

Q24. How long does air receiver, dehumidifier dismantling take?
Man hours ____________________
I do not know.

Q25. How long does Air Condition (A/C) system (cabins are not included) dismantling take?
Man hours ____________________
I do not know.

Q26. How long does refrigeration unit (cabinets are except) dismantling take?
Man hours ____________________
I do not know.

Q27. How long does Engine Control Room (E.C.R.) A/C unit dismantling take?
Man hours ____________________
I do not know.

Q28. How long does sanitary system and equipment dismantling take?
Man hours ____________________
I do not know.

Q29. How long does Sewage Treatment System (all parts, except cabins) dismantling take?
Man hours ____________________
I do not know.

Q30. How long does Oily Water (Bilge Water) Separator dismantling take?
Man hours ____________________
I do not know.

Q31. How long does all Engine Room equipment's control unit panels dismantling take?
Man hours ____________________
I do not know.

Q32. How long does Engine Control Room (ECR) equipment (panels, control units, furniture are not included) dismantling take?
Man hours ____________________
I do not know.

Q33. How long does Engine Room Crane(s) (generally one big which is located on M/E) dismantling?
Man hours ____________________
I do not know.

Q34. How long does Workshop (all equipment, machines) dismantling take?
Man Hours ____________________
I do not know.

Q35. How long does all Spare Parts dismantling/transporting take?
Man hours ____________________
I do not know.

Q36. How long does all pumps (s/w, f/w, etc,) dismantling take?
Man hours ____________________
I do not know.

Q37. How long does Fire-fighting Equipment (fixed) dismantling take?
Man hours ____________________
I do not know.
Q38.
Is there any information missing in this survey? Is there any suggestion would you like to share with the authors of this survey?

Question numbers						**Survey Results (man-hours)**					
1	16	12	10	20	16	16	16	10	-	10	20
2	16	12	12	20	12	12	12	6	6	6	20
3	16	12	12	16	12	16	16	3	20	3	20
4	16	10	12	16	16	12	16	6	4	4	16
5	8	8	10	8	10	8	12	2	-	2	12
6	6	5	6	8	12	16	16	6	24	5	24
7	3	2	2	2	4	4	3	4	-	2	4
8	3	2	2	4	6	12	8	4	8	2	12
9	16	12	12	20	16	24	17	5	40	5	40
10	16	12	12	16	8	10	12	2	2	2	16
11	2	2	2	3	4	8	6	2	10	2	10
12	4	3	3	4	4	6	6	3	4	3	6
13	6	8	8	8	10	6	12	4	3	3	12
14	16	12	16	16	12	24	24	8	-	8	24
15	6	4	6	8	12	24	24	8	-	4	24
16	6	3	4	8	12	16	16	4	-	3	16
17	40	24	32	40	16	32	48	8	48	8	48
18	4	5	5	6	10	8	8	4	16	4	16

19	3	2	2	3	2	4	4	2	6	2	6
20	8	4	6	6	8	12	12	2	12	2	12
21	5	3	4	6	8	12	12	2	8	2	12
22	3	2	2	4	10	8	8	2	8	2	10
23	4	4	4	6	8	12	16	10	20	4	20
24	4	3	4	6	8	12	16	9	10	3	16
25	3	2	3	4	6	8	9	2	8	2	9
26	16	24	16	24	24	32	32	8	-	8	32
27	16	20	16	24	24	32	40	5	-	5	40
28	1	2	2	4	2	6	4	3	-	1	6
29	8	10	12	8	16	12	10	4	-	4	16
30	6	8	8	10	12	9	16	3	-	3	16
31	12	10	12	16	16	16	24	5	48	5	48
32	8	5	8	8	16	16	12	6	18	5	18

D1.6 Plasma cutting manufacturer data

D1.6.1 Hypertherm Powermax 85

Recommended (Hypertherm, 2017a)

Thickness (mm)	Cutting speed (mm/min)
25	500
32	250
38	125

Pierce capacity: 19 mm

Maximum cut speed (lab results)

Thickness (mm)	Cutting speed (mm/min)
6	5500
12	2000
19	900
25	550
32	330

Production speeds are approximately 80% of maximum cut speed (hypertherm.com, 2017).
Recommended gas inlet flow rate/pressure Cutting: 400 scfh, 6.7 scfm @ 85 psi

HYPERTHERM 85 PLASMA			
Material Thickness (mm)	Pierce Delay (sec)	Cut speed for best quality (mm/min)	Cut speed for production (mm/min)
3	0.1	6800	9200
4	0.2	5650	7300
6	0.5	3600	4400
8	0.5	2500	3100
10	0.5	1680	2070
12	0.7	1280	1600
16	1.0	870	930
20	1.5	570	680
25	Edge start	350	450
30	Edge start	200	300

D1.6.2 Hypertherm Powermax 125

Recommended (Hypertherm, 2017b)

Thickness (mm)	Cutting speed (mm/min)
38	457
44	250
57	125

Pierce capacity: 25 mm

Maximum cut speed (lab results)

Thickness (mm)	Cutting speed (mm/min)
6	7160
10	4390

12	2950
16	2100
20	1470
22	1170
25	940
32	610
38	457

Production speeds are approximately 80% of maximum cut speed (hypertherm.com, 2017).
Recommended gas inlet flow rate / pressure Cutting: 260 l/min (550 scfh) @5.9 bar (85 psi)

HYPERTHERM 125 PLASMA			
Material Thickness (mm)	Pierce Delay (sec)	Cut speed for best quality (mm/min)	Cut speed for production (mm/min)
6	0.2	4980	5960
8	0.3	3800	4570
10	0.4	2750	3330
12	0.5	2050	2510
16	0.6	1260	1660
20	2.0	980	1140
25	3.5	610	780
30	Edge start	460	580
32	Edge start	400	500
35	Edge start	340	430
40	Edge start	240	310

D1.6.3 Plasma cutting Hourly cost:

For the calculation of the plasma cutting hourly cost, framework of Hypertherm was used (Hypertherm, 2015).

D 1.6.3.1.Electricity Cost

Non-household electricity price in EU in average was €0.114 per kWh (eurostat, 2018).

- Powermax 85

133 V at 85 A;

$$133 \times 85 = 11.3\ kVA$$

0.85 power supply efficiency factor

$$11.3\ kVA \times 0.85 = 9.605\ kW$$

Therefore the hourly cost;

$$9.605 \times 0.114 = €\ \mathbf{1.09}$$

- Powermax 125

164 V at 125 A;

$$164 \times 125 = 20.5\ kVA$$

0.85 power supply efficiency factor

$$20.5\ kVA \times 0.85 = 17.425\ kW$$

Therefore the hourly cost;

$$17.425 \times 0.114 = €\ \mathbf{1.98}$$

D. 1.6.3.2 Air Cost

Cost of the air; 10.16 m3 = € 40.84 (Price on 8th February 2018) (1GBP = 1.14 EUR) (BOC, 2018)
Therefore, price per litre is 0.00402 €/lt

- Powermax 85

Gas consumption of Powermax 85: 189 standard litre per minute (needs to be converted to operation standard) (grabbed from the manual (Hypertherm, 2017a))
Conversion to operation consumption;
LPM: liters per minute
SLPM: standard liters per minute

$1\ LPM = 1\ SLPM \times \frac{T_{gas}}{273.15\ K} \times \frac{14.504\ psi}{P_{gas}}$ (dgflo, n.d.)
Following the conversion consumption rate is 35.36 l/min. Therefore, hourly cost is **€8.53**

- Powermax 125

Gas consumption of Powermax 125: 260 standard litre per minute (needs to be converted to operation standard) (grabbed from the manual (Hypertherm, 2017b))
Following the conversion consumption rate is 48.65 l/min. Therefore, hourly cost is **€11.73**

D.1.6.3.3 Consumable Cost

In order to calculate the consumable cost Torchmate's methodology was followed and cost of the consumables for
data collection block is **€2.49** (Torchmate, n.d.)
accommodation area block is **€4.21** (Torchmate, n.d.)
double bottom block is **€9.84** (Torchmate, n.d.)

Powermax 85 total cost per hour

€ 9.62 hour rate + consumable cost for operation

Powermax 125 total cost per hour

€ 13.72 hour rate + consumable cost for operation

D1.7. Other Cost Data

Worker hourly rate: €15.99
Manager hourly cost: €25.99
Foreman hourly cost: €18.00
Crane hourly cost: €14.00
Polygrab hourly cost: €10
Operator hourly cost: €18.00
Initial investment Powermax 125: €6,789.98
Initial investment Powermax 85: €4070.61
Initial investment Long Torch €1368.12
Oxy-Fuel cutting hourly rate: **€7**

D1.8 Engine Room Equipment Revenue

Element	**CTD**	Value (€)
MMPP MAN B&W 6S50 MC-C	1	120000
MMAA Wartsila auxiliary engines 645 kwa	3	45000
Propeller fixed pitch	1	35000
DO separator	1	4000
Oil separator	2	4000
FO separator	2	16000
Air Compressors (starting)+service compressor+emergency compressor	4	4000
Bow Anchors	2	6000
Anchor chain (27.5 mt)	8	26000
Free fall lifeboat	1	23000
Life rafts	3	300
Galley equipment	1	3000
Ballast pumps	2	5000
Steering gear and manouvering machinery	1	10000
Emergency diesel generator	1	2500
Bilge water separator	1	1000
Sewage treatment unit	1	1000
Safety equipment (escape equiments...etc)	1	3000
Heat exchangers	4	12000
Others (spares, smaller equipment, others)		€50000
		€370800

D1.9 Non-ferrous metal distribution

Steel	85.00%
Aluminium	0.10%
INOX	0.25%
Brass	0.10%
Copper	0.10%
Bronze	0.25%
Cables	0.25%

D2. Chapter 7 Arena Models and Details

D2.1 Validation Model

D2.1.1 Validation of model-Worker Data

Create Block

Name	Entity Type	Type	Value	Units	Entities per Arrival	Max arrivals	First Creation
Block from primary cutting zone	Accommodation block	Random (Expo)	1	Hours	1	1	0.0

Record Blocks

Name	Type	Type	Value	Counter name	Tally Name
Record incoming block	Count	Attribute 1	1	No of block	
Record outputs	Time Interval	Arrival time	1		total time
	Count	Attribute 1	1	No of plate out	

Assign Block

Name	Type	Attribute name	Entity Picture	
Assign time and picture	Attribute	Arrival time	Picture.Report	TNOW
	Entity Picture		Picture.Package	

Station Block

Name	Station Type	Station Name	Parent Activity Area	Associated Intersectipn
Secondary cutting	Station	Secondary cutting zone		

Dispose Block

Name	Record Entity Statistics
Dispose 1	Yes

Submodel Block

Submodel Name : Cutting in secondary zone
Number of entry points : 1
Number of exit points : 1

Seize (Submodel)

Name	Allocation	Priority	Queue Type	Queue Name	Type	Resource name	Units to seize
Seize cutter and torch 1	Other	Medium(2)	Queue	Seize cutter and torch 1.Queue	Resource	Torch	1
						Cutting team	1
Seize cutter and torch 2	Other	Medium(2)	Queue	Seize cutter and torch 2.Queue	Resource	Torch	1
						Cutting team	1
Seize cutter and torch 3	Other	Medium(2)	Queue	Seize cutter and torch 3.Queue	Resource	Torch	1
						Cutting team	1

Delay (Submodel)

Delay blocks were used in this model in order to represent the repositioning of the worker during cutting operation.

Name	Allocation	Delay Time	Units	Name	Allocation	Delay Time	Units
Delay 1	Other	45	Seconds	Delay 18	Other	8	Seconds
Delay 2	Other	14	Seconds	Delay 19	Other	9	Seconds
Delay 3	Other	6	Seconds	Delay 20	Other	4	Seconds
Delay 4	Other	7	Seconds	Delay 21	Other	27	Seconds
Delay 5	Other	9	Seconds	Delay 22	Other	44	Seconds
Delay 6	Other	2	Seconds	Delay 23	Other	5	Seconds
Delay 7	Other	2	Seconds	Delay 24	Other	23	Seconds
Delay 9	Other	4	Seconds	Delay 25	Other	26	Seconds
Delay 10	Other	8	Seconds	Delay 26	Other	2	Seconds
Delay 11	Other	4	Seconds	Delay 27	Other	15	Seconds
Delay 12	Other	6	Seconds	Delay 28	Other	2	Seconds
Delay 13	Other	27	Seconds	Delay 29	Other	10	Seconds
Delay 14	Other	2	Seconds	Delay 30	Other	2	Seconds
Delay 15	Other	8	Seconds	Delay 31	Other	4	Seconds
Delay 16	Other	4	Seconds	Delay 32	Other	5	Seconds
Delay 17	Other	2	Seconds				

Process (Submodel)

Process block is used to represent the cutting procedure.

Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Cutline 1	Delay	Constant	450	Cutline 16	Delay	Constant	175
Cutline 2	Delay	Constant	62	Cutline 17	Delay	Constant	174
Cutline 3	Delay	Constant	59	Cutline 18	Delay	Constant	146
Cutline 4	Delay	Constant	62	Cutline 19	Delay	Constant	114
Cutline 5	Delay	Constant	64	Cutline 20	Delay	Constant	140
Cutline 6	Delay	Constant	92	Cutline 21	Delay	Constant	145
Cutline 7	Delay	Constant	66	Cutline 22	Delay	Constant	118
Cutline 8	Delay	Constant	173	Cutline 23	Delay	Constant	137
Cutline 9	Delay	Constant	18	Cutline 24	Delay	Constant	180
Cutline 10	Delay	Constant	9	Cutline 25	Delay	Constant	91
Cutline 11	Delay	Constant	25	Cutline 26	Delay	Constant	147
Cutline 12	Delay	Constant	173	Cutline 27	Delay	Constant	90
Cutline 13	Delay	Constant	16	Cutline 28	Delay	Constant	148
Cutline 14	Delay	Constant	18	Cutline 29	Delay	Constant	150
Cutline 15	Delay	Constant	21	Cutline 30	Delay	Constant	95

Release (Submodel)

Name	Type	Resource Name	Units to release
Release resources	Resource	Torch	1
	Resource	Cutting team	1
Release resources 2	Resource	Torch	1
	Resource	Cutting team	1
Release resources 3	Resource	Torch	1
	Resource	Cutting team	1

D2.1.2 Validation of model-Manufacturer Data

Delay (Submodel)

Delay blocks were used in this model in order to represent the repositioning of the worker during cutting operation.

Name	Allocation	Delay Time	Units	Name	Allocation	Delay Time	Units
Delay 1	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 17	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 18	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 3	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 19	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 4	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 20	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 5	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 21	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 6	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 22	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 7	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 23	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 8	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 24	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 9	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 25	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 10	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 26	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 11	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 27	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 12	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 28	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 13	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 29	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 14	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 30	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 15	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Delay 31	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Delay 16	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds				

Process (Submodel)

Process block is used to represent the cutting procedure. Value cell is the total of the pierce and cutting duration for each cutline

Name	Action	Unit	Value	Name	Action	Unit	Value
Cutline 1	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 16	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 2	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 17	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 3	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 18	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 4	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 19	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 5	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 20	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 6	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 21	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 7	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 22	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 8	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 23	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 9	Delay	Seconds	NORM(9.5, 2.33) + 8.7	Cutline 24	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 10	Delay	Seconds	NORM(9.5, 2.33) + 8.7	Cutline 25	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 11	Delay	Seconds	NORM(9.5, 2.33) + 8.7	Cutline 26	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 12	Delay	Seconds	8.5 + 8 * BETA(0.97	Cutline 27	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 13	Delay	Seconds	NORM(9.5, 2.33) + 8.7	Cutline 28	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 14	Delay	Seconds	NORM(9.5, 2.33) + 8.7	Cutline 29	Delay	Seconds	8.5 + 8 * BETA(0.97
Cutline 15	Delay	Seconds	NORM(9.5, 2.33) + 8.7	Cutline 30	Delay	Seconds	8.5 + 8 * BETA(0.97

D2.1.3 Validation Model – Plasma (Powermax 85) Data

Process (Submodel)

Process block is used to represent the cutting procedure. Value cell is the total of the pierce and cutting duration for each cutline. Value of the cutting duration is calculated through;

$$Value = (Cutting\ length\ \times Cutting\ speed) + Piercing\ duration$$

In this model, one second piercing duration was added to each cutting line.

Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Cutline 1	Delay	Constant	223.77	Cutline 16	Delay	Constant	104.96
Cutline 2	Delay	Constant	18.82	Cutline 17	Delay	Constant	104.96
Cutline 3	Delay	Constant	18.82	Cutline 18	Delay	Constant	75.26
Cutline 4	Delay	Constant	18.82	Cutline 19	Delay	Constant	60.41
Cutline 5	Delay	Constant	18.82	Cutline 20	Delay	Constant	75.26
Cutline 6	Delay	Constant	18.82	Cutline 21	Delay	Constant	75.26
Cutline 7	Delay	Constant	18.82	Cutline 22	Delay	Constant	62.19
Cutline 8	Delay	Constant	104.96	Cutline 23	Delay	Constant	75.26
Cutline 9	Delay	Constant	6.94	Cutline 24	Delay	Constant	75.26
Cutline 10	Delay	Constant	6.94	Cutline 25	Delay	Constant	49.71
Cutline 11	Delay	Constant	6.94	Cutline 26	Delay	Constant	75.26

Cutline 12	Delay	Constant	104.96	Cutline 27	Delay	Constant	43.77
Cutline 13	Delay	Constant	6.94	Cutline 28	Delay	Constant	75.26
Cutline 14	Delay	Constant	6.94	Cutline 29	Delay	Constant	75.26
Cutline 15	Delay	Constant	6.94	Cutline 30	Delay	Constant	43.77

D2.1.4 Validation Model – Plasma (Powermax 125) Data

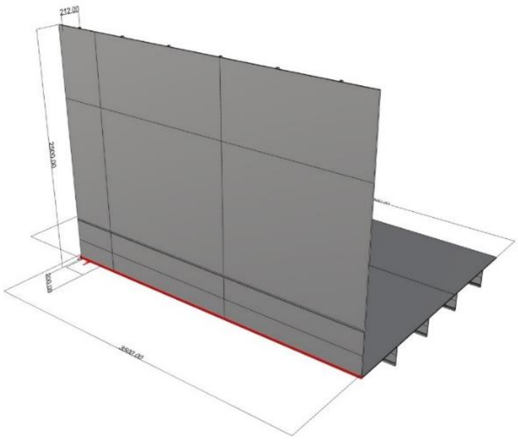
Process (Submodel)

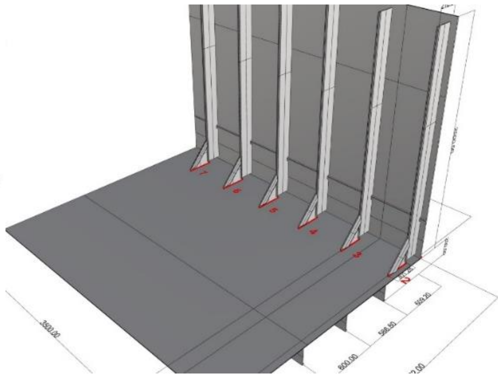
In this model, one second piercing duration was added to each cutting line.

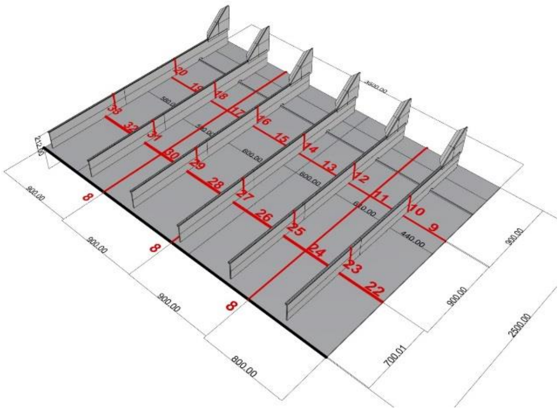
Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Cutline 1	Delay	Constant	124.63	Cutline 16	Delay	Constant	58.69
Cutline 2	Delay	Constant	10.89	Cutline 17	Delay	Constant	58.69
Cutline 3	Delay	Constant	10.89	Cutline 18	Delay	Constant	42.21
Cutline 4	Delay	Constant	10.89	Cutline 19	Delay	Constant	33.97
Cutline 5	Delay	Constant	10.89	Cutline 20	Delay	Constant	42.21
Cutline 6	Delay	Constant	10.89	Cutline 21	Delay	Constant	42.21
Cutline 7	Delay	Constant	10.89	Cutline 22	Delay	Constant	34.96
Cutline 8	Delay	Constant	58.69	Cutline 23	Delay	Constant	42.21
Cutline 9	Delay	Constant	4.30	Cutline 24	Delay	Constant	42.21
Cutline 10	Delay	Constant	4.30	Cutline 25	Delay	Constant	28.03
Cutline 11	Delay	Constant	4.30	Cutline 26	Delay	Constant	42.21
Cutline 12	Delay	Constant	58.69	Cutline 27	Delay	Constant	24.74
Cutline 13	Delay	Constant	4.30	Cutline 28	Delay	Constant	42.21
Cutline 14	Delay	Constant	4.30	Cutline 29	Delay	Constant	42.21
Cutline 15	Delay	Constant	4.30	Cutline 30	Delay	Constant	24.74

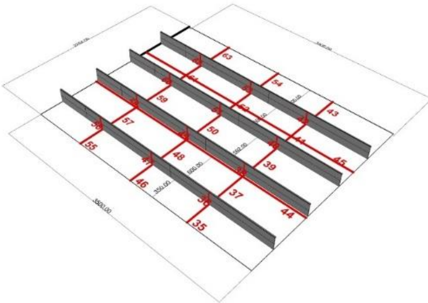
D2.2 Accommodation Area Block Model

D2.2.1 Cut lines









D2.2.2 Cutting lengths

Cut line #	Length	Unit	Cut line #	Length	Unit
Cut line 1	3500	mm	Cut line 32	600	mm
Cut line 2	301	mm	Cut line 33	200	mm
Cut line 3	301	mm	Cut line 34	70	mm
Cut line 4	301	mm	Cut line 35	350	mm
Cut line 5	301	mm	Cut line 36	200	mm
Cut line 6	301	mm	Cut line 37	600	mm
Cut line 7	301	mm	Cut line 38	200	mm
Cut line 8.1	2500	mm	Cut line 39	592	mm
Cut line 8.2	2500	mm	Cut line 40	200	mm
Cut line 8.3	2500	mm	Cut line 41	600	mm
Cut line 9	440	mm	Cut line 42	200	mm
Cut line 10	200	mm	Cut line 43	600	mm
Cut line 11	610	mm	Cut line 44	3500	mm
Cut line 12	200	mm	Cut line 45	3500	mm
Cut line 13	600	mm	Cut line 46	350	mm
Cut line 14	200	mm	Cut line 47	200	mm
Cut line 15	600	mm	Cut line 48	600	mm
Cut line 16	200	mm	Cut line 49	200	mm

Cut line 17	590	mm	Cut line 50	592	mm
Cut line 18	200	mm	Cut line 51	200	mm
Cut line 19	580	mm	Cut line 52	600	mm
Cut line 20	200	mm	Cut line 53	200	mm
Cut line 21	70	mm	Cut line 54	600	mm
Cut line 22	440	mm	Cut line 55	350	mm
Cut line 23	200	mm	Cut line 56	200	mm
Cut line 24	600	mm	Cut line 57	600	mm
Cut line 25	200	mm	Cut line 58	200	mm
Cut line 26	600	mm	Cut line 59	592	mm
Cut line 27	200	mm	Cut line 60	200	mm
Cut line 28	600	mm	Cut line 61	600	mm
Cut line 29	200	mm	Cut line 62	200	mm
Cut line 30	600	mm	Cut line 63	600	mm
Cut line 31	200	mm			

D2.2.3 ARENA model for the case with no surface cleaning

Delay (Submodel)

Delay blocks were used in this model in order to represent the repositioning of the worker during cutting operation.

Name	Delay Time	Units	Name	Delay Time	Units
Repos 1	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 34	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 2	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 35	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 3	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 36	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 4	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 37	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 5	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 38	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 6	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 39	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 7	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 40	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 8	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 41	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 9	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 42	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 10	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 43	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 11	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 44	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 12	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 45	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 13	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 46	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 14	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 47	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 15	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 48	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 16	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 49	1.5 + 44 * BETA(0.478, 1.19)	Seconds

Repos 17	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 50	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 18	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 51	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 19	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 52	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 20	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 53	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 21	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 54	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 22	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 55	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 23	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 56	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 24	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 57	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 25	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 58	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 26	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 59	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 27	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 60	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 28	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 61	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 29	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 62	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 30	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 63	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 31	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 64	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 32	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Ignition	TRIA (10,15,20)	Seconds
Repos 33	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Separate	1	Minutes

D2.2.3.1 Oxyfuel

Process (Submodel)

Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Cutline 1	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 350	Cut line 31	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cutline 2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30.128	Cut line 32	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cutline 3	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30.128	Cut line 33	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cutline 4	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30.128	Cut line 34	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 7
Cutline 5	Delay	Expression	8.5 + 8 * BETA(0.97	Cut line 35	Delay	Expression	8.5 + 8 * BETA(0.97

			8, 1.1) + 30.128				8, 1.1) + 35
Cutline 6	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30.128	Cut line 36	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cutline 7	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30.128	Cut line 37	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 8.1	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 250	Cut line 38	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 8.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 250	Cut line 39	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 8.3	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 250	Cut line 40	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 9	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 44	Cut line 41	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 10	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 42	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 11	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 61	Cut line 43	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 12	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 44	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 350
Cut line 13	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60	Cut line 45	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 350
Cut line 14	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 46	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 35
Cut line 15	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60	Cut line 47	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40

Cut line 16	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60	Cut line 48	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 17	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59	Cut line 49	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 18	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 50	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59.2
Cut line 19	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 58	Cut line 51	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 20	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 52	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 21	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 7	Cut line 53	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 22	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 44	Cut line 54	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 23	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 55	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 35
Cut line 24	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60	Cut line 56	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 25	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 57	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 26	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60	Cut line 58	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 27	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 59	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 28	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60	Cut line 60	Delay	Expression	8.5 + 8 * BETA(0.97

							8, 1.1) + 40
Cut line 29	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 61	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 30	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60	Cut line 62	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
				Cut line 63	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60

D2.2.3.2 Plasma 85

Process (Submodel)

In this model, one second piercing duration was added to each cutting line.

Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Cutline 1	Delay	Constant	208.92	Cut line 31	Delay	Constant	24.76
Cutline 2	Delay	Constant	18.9	Cut line 32	Delay	Constant	36.64
Cutline 3	Delay	Constant	18.9	Cut line 33	Delay	Constant	24.76
Cutline 4	Delay	Constant	18.9	Cut line 34	Delay	Constant	5.16
Cutline 5	Delay	Constant	18.9	Cut line 35	Delay	Constant	21.79
Cutline 6	Delay	Constant	18.9	Cut line 36	Delay	Constant	24.76
Cutline 7	Delay	Constant	18.9	Cut line 37	Delay	Constant	36.64
Cut line 8.1	Delay	Constant	149.51	Cut line 38	Delay	Constant	24.76
Cut line 8.2	Delay	Constant	149.51	Cut line 39	Delay	Constant	36.17
Cut line 8.3	Delay	Constant	149.51	Cut line 40	Delay	Constant	24.76
Cut line 9	Delay	Constant	27.14	Cut line 41	Delay	Constant	36.64
Cut line 10	Delay	Constant	24.76	Cut line 42	Delay	Constant	24.76
Cut line 11	Delay	Constant	37.24	Cut line 43	Delay	Constant	36.64
Cut line 12	Delay	Constant	24.76	Cut line 44	Delay	Constant	208.92
Cut line 13	Delay	Constant	36.64	Cut line 45	Delay	Constant	208.92
Cut line 14	Delay	Constant	24.76	Cut line 46	Delay	Constant	21.79
Cut line 15	Delay	Constant	36.64	Cut line 47	Delay	Constant	24.76
Cut line 16	Delay	Constant	24.76	Cut line 48	Delay	Constant	36.64

Cut line 17	Delay	Constant	36.05	Cut line 49	Delay	Constant	24.76
Cut line 18	Delay	Constant	24.76	Cut line 50	Delay	Constant	36.17
Cut line 19	Delay	Constant	35.46	Cut line 51	Delay	Constant	24.76
Cut line 20	Delay	Constant	24.76	Cut line 52	Delay	Constant	36.64
Cut line 21	Delay	Constant	5.16	Cut line 53	Delay	Constant	24.76
Cut line 22	Delay	Constant	27.14	Cut line 54	Delay	Constant	36.64
Cut line 23	Delay	Constant	24.76	Cut line 55	Delay	Constant	21.79
Cut line 24	Delay	Constant	36.64	Cut line 56	Delay	Constant	24.76
Cut line 25	Delay	Constant	24.76	Cut line 57	Delay	Constant	36.64
Cut line 26	Delay	Constant	36.64	Cut line 58	Delay	Constant	24.76
Cut line 27	Delay	Constant	24.76	Cut line 59	Delay	Constant	36.17
Cut line 28	Delay	Constant	36.64	Cut line 60	Delay	Constant	24.76
Cut line 29	Delay	Constant	24.76	Cut line 61	Delay	Constant	36.64
Cut line 30	Delay	Constant	36.64	Cut line 62	Delay	Constant	24.76
				Cut line 63	Delay	Constant	36.64

D2.2.3.3 Plasma 125

Process (Submodel)

In this model, one second piercing duration was added to each cutting line.

Name	Action	Allocation	Value	Name	Action	Allocation	Value
Cutline 1	Delay	Value Added	116.38	Cut line 33	Delay	Value Added	14.19
Cutline 2	Delay	Value Added	10.93	Cut line 34	Delay	Value Added	3.31
Cutline 3	Delay	Value Added	10.93	Cut line 35	Delay	Value Added	12.54
Cutline 4	Delay	Value Added	10.93	Cut line 36	Delay	Value Added	14.19
Cutline 5	Delay	Value Added	10.93	Cut line 37	Delay	Value Added	20.78
Cutline 6	Delay	Value Added	10.93	Cut line 38	Delay	Value Added	14.19
Cutline 7	Delay	Value Added	10.93	Cut line 39	Delay	Value Added	20.52
Cut line 8.1	Delay	Value Added	83.42	Cut line 40	Delay	Value Added	14.19
Cut line 8.2	Delay	Value Added	83.42	Cut line 41	Delay	Value Added	20.78
Cut line 8.3	Delay	Value Added	82.42	Cut line 42	Delay	Value Added	14.19
Cut line 9	Delay	Value Added	15.51	Cut line 43	Delay	Value Added	20.78
Cut line 10	Delay	Value Added	14.19	Cut line 44	Delay	Value Added	116.38

Cut line 11	Delay	Value Added	21.11	Cut line 45	Delay	Value Added	116.38
Cut line 12	Delay	Value Added	14.19	Cut line 46	Delay	Value Added	12.54
Cut line 13	Delay	Value Added	20.78	Cut line 47	Delay	Value Added	14.19
Cut line 14	Delay	Value Added	14.19	Cut line 48	Delay	Value Added	20.78
Cut line 15	Delay	Value Added	20.78	Cut line 49	Delay	Value Added	14.19
Cut line 16	Delay	Value Added	14.19	Cut line 50	Delay	Value Added	20.52
Cut line 17	Delay	Value Added	20.45	Cut line 51	Delay	Value Added	14.19
Cut line 18	Delay	Value Added	14.19	Cut line 52	Delay	Value Added	20.78
Cut line 19	Delay	Value Added	20.12	Cut line 53	Delay	Value Added	14.19
Cut line 20	Delay	Value Added	14.19	Cut line 54	Delay	Value Added	20.78
Cut line 21	Delay	Value Added	3.31	Cut line 55	Delay	Value Added	12.54
Cut line 22	Delay	Value Added	15.51	Cut line 56	Delay	Value Added	14.19
Cut line 23	Delay	Value Added	14.19	Cut line 57	Delay	Value Added	20.78
Cut line 24	Delay	Value Added	20.78	Cut line 58	Delay	Value Added	14.19
Cut line 25	Delay	Value Added	14.19	Cut line 59	Delay	Value Added	20.52
Cut line 26	Delay	Value Added	20.78	Cut line 60	Delay	Value Added	14.19
Cut line 27	Delay	Value Added	14.19	Cut line 61	Delay	Value Added	20.78
Cut line 28	Delay	Value Added	20.78	Cut line 62	Delay	Value Added	14.19
Cut line 29	Delay	Value Added	14.19	Cut line 63	Delay	Value Added	20.78
Cut line 30	Delay	Value Added	20.78				
Cut line 31	Delay	Value Added	14.19				
Cut line 32	Delay	Value Added	20.78				

D2.3.3.3 Waterjet

Process (Submodel)

Name	Action	Delay Type	Allocation	Value	Name	Action	Delay Type	Allocation	Value
Cutline 1	Delay	Constant	Value Added	878.6611	Cut line 33	Delay	Constant	Value Added	50.20921
Cutline 2	Delay	Constant	Value Added	75.63515	Cut line 34	Delay	Constant	Value Added	17.57322
Cutline 3	Delay	Constant	Value Added	75.63515	Cut line 35	Delay	Constant	Value Added	87.86611
Cutline 4	Delay	Constant	Value Added	75.63515	Cut line 36	Delay	Constant	Value Added	50.20921

Cutline 5	Delay	Constant	Value Added	75.63515
Cutline 6	Delay	Constant	Value Added	75.63515
Cutline 7	Delay	Constant	Value Added	75.63515
Cut line 8.1	Delay	Constant	Value Added	627.6151
Cut line 8.2	Delay	Constant	Value Added	627.6151
Cut line 8.3	Delay	Constant	Value Added	627.6151
Cut line 9	Delay	Constant	Value Added	110.4603
Cut line 10	Delay	Constant	Value Added	50.20921
Cut line 11	Delay	Constant	Value Added	153.1381
Cut line 12	Delay	Constant	Value Added	50.20921
Cut line 13	Delay	Constant	Value Added	150.6276
Cut line 14	Delay	Constant	Value Added	50.20921
Cut line 15	Delay	Constant	Value Added	150.6276
Cut line 16	Delay	Constant	Value Added	50.20921
Cut line 17	Delay	Constant	Value Added	148.1172
Cut line 18	Delay	Constant	Value Added	50.20921
Cut line 19	Delay	Constant	Value Added	145.6067
Cut line 20	Delay	Constant	Value Added	50.20921
Cut line 21	Delay	Constant	Value Added	17.57322
Cut line 22	Delay	Constant	Value Added	110.4603
Cut line 23	Delay	Constant	Value Added	50.20921
Cut line 37	Delay	Constant	Value Added	150.6276
Cut line 38	Delay	Constant	Value Added	50.20921
Cut line 39	Delay	Constant	Value Added	148.6192
Cut line 40	Delay	Constant	Value Added	50.20921
Cut line 41	Delay	Constant	Value Added	150.6276
Cut line 42	Delay	Constant	Value Added	50.20921
Cut line 43	Delay	Constant	Value Added	150.6276
Cut line 44	Delay	Constant	Value Added	878.6611
Cut line 45	Delay	Constant	Value Added	878.6611
Cut line 46	Delay	Constant	Value Added	87.86611
Cut line 47	Delay	Constant	Value Added	50.20921
Cut line 48	Delay	Constant	Value Added	150.6276
Cut line 49	Delay	Constant	Value Added	50.20921
Cut line 50	Delay	Constant	Value Added	148.6192
Cut line 51	Delay	Constant	Value Added	50.20921
Cut line 52	Delay	Constant	Value Added	150.6276
Cut line 53	Delay	Constant	Value Added	50.20921
Cut line 54	Delay	Constant	Value Added	150.6276
Cut line 55	Delay	Constant	Value Added	87.86611
Cut line 56	Delay	Constant	Value Added	50.20921
Cut line 57	Delay	Constant	Value Added	150.6276

Cut line 24	Delay	Constant	Value Added	150.6276
Cut line 25	Delay	Constant	Value Added	50.20921
Cut line 26	Delay	Constant	Value Added	150.6276
Cut line 27	Delay	Constant	Value Added	50.20921
Cut line 28	Delay	Constant	Value Added	150.6276
Cut line 29	Delay	Constant	Value Added	50.20921
Cut line 30	Delay	Constant	Value Added	150.6276
Cut line 31	Delay	Constant	Value Added	50.20921
Cut line 32	Delay	Constant	Value Added	150.6276
Cut line 58	Delay	Constant	Value Added	50.20921
Cut line 59	Delay	Constant	Value Added	148.6192
Cut line 60	Delay	Constant	Value Added	50.20921
Cut line 61	Delay	Constant	Value Added	150.6276
Cut line 62	Delay	Constant	Value Added	50.20921
Cut line 63	Delay	Constant	Value Added	150.6276

D2.2.4 ARENA model for the case with surface cleaning

D2.2.4.1 Surface Cleaning Submodel

Seize

Name	Allocation	Priority	Queue Type	Queue Name	Type	Resource name	Units to seize
Seize cutter and surface cleaning tool	Other	Medium(2)	Queue	Seize cutter and surface cleaning tool.Queue	Resource	SC	1
						Cutting team	1

Delay

Name	Allocation	Delay Time	Units	Name	Allocation	Delay Time	Units
Setup wj	Other	10	Minutes	R32	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R1	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R33	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R34	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R3	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R35	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R4	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R36	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R5	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R37	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R6	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R38	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds

R7	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R39	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R8	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R40	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R9	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R41	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R10	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R42	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R11	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R43	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R12	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R44	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R13	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R45	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R14	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R46	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R15	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R47	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R16	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R48	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R17	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R49	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R18	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R50	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R19	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R51	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R20	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R52	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R21	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R53	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R22	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R54	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R23	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R55	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R24	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R56	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R25	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R57	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R26	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R58	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R27	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R59	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R28	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R60	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R29	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R61	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R30	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R62	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds

R31	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	R63	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds

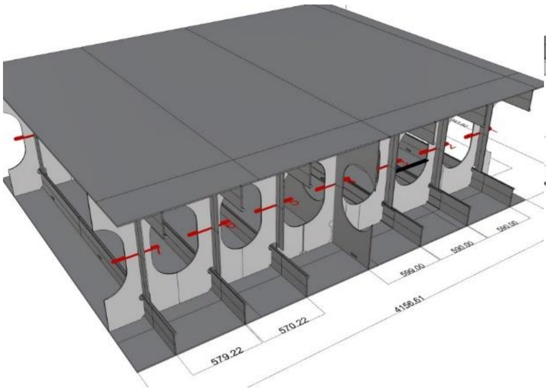
Process

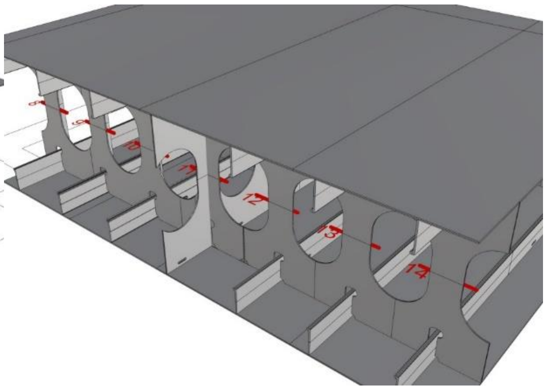
Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Clean line 1	Delay	Constant	233.3333	Clean line 33	Delay	Constant	13.33333
Clean line 2	Delay	Constant	20.08533	Clean line 34	Delay	Constant	4.666667
Clean line 3	Delay	Constant	20.08533	Clean line 35	Delay	Constant	23.33333
Clean line 4	Delay	Constant	20.08533	Clean line 36	Delay	Constant	13.33333
Clean line 5	Delay	Constant	20.08533	Clean line 37	Delay	Constant	40
Clean line 6	Delay	Constant	20.08533	Clean line 38	Delay	Constant	13.33333
Clean line 7	Delay	Constant	20.08533	Clean line 39	Delay	Constant	39.46667
Clean line 8	Delay	Constant	166.6667	Clean line 40	Delay	Constant	13.33333
Clean line 9	Delay	Constant	29.33333	Clean line 41	Delay	Constant	40
Clean line 10	Delay	Constant	13.33333	Clean line 42	Delay	Constant	13.33333
Clean line 11	Delay	Constant	40.66667	Clean line 43	Delay	Constant	40
Clean line 12	Delay	Constant	13.33333	Clean line 44	Delay	Constant	233.3333
Clean line 13	Delay	Constant	40	Clean line 45	Delay	Constant	233.3333
Clean line 14	Delay	Constant	13.33333	Clean line 46	Delay	Constant	23.33333
Clean line 15	Delay	Constant	40	Clean line 47	Delay	Constant	13.33333
Clean line 16	Delay	Constant	13.33333	Clean line 48	Delay	Constant	40
Clean line 17	Delay	Constant	39.33333	Clean line 49	Delay	Constant	13.33333
Clean line 18	Delay	Constant	13.33333	Clean line 50	Delay	Constant	39.46667
Clean line 19	Delay	Constant	38.66667	Clean line 51	Delay	Constant	13.33333
Clean line 20	Delay	Constant	13.33333	Clean line 52	Delay	Constant	40
Clean line 21	Delay	Constant	4.666667	Clean line 53	Delay	Constant	13.33333
Clean line 22	Delay	Constant	29.33333	Clean line 54	Delay	Constant	40
Clean line 23	Delay	Constant	13.33333	Clean line 55	Delay	Constant	23.33333
Clean line 24	Delay	Constant	40	Clean line 56	Delay	Constant	13.33333
Clean line 25	Delay	Constant	13.33333	Clean line 57	Delay	Constant	40
Clean line 26	Delay	Constant	40	Clean line 58	Delay	Constant	13.33333
Clean line 27	Delay	Constant	13.33333	Clean line 59	Delay	Constant	39.46667
Clean line 28	Delay	Constant	40	Clean line 60	Delay	Constant	13.33333

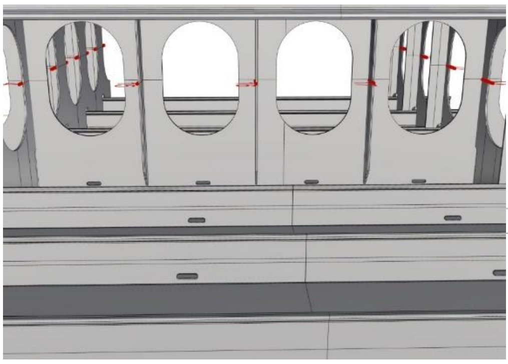
Clean line 29	Delay	Constant	13.33333	Clean line 61	Delay	Constant	40
Clean line 30	Delay	Constant	40	Clean line 62	Delay	Constant	13.33333
Clean line 31	Delay	Constant	13.33333	Clean line 63	Delay	Constant	40
Clean line 32	Delay	40					

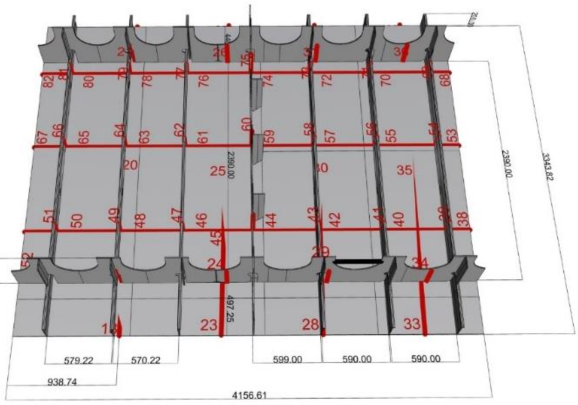
D2.3 Double Bottom Block

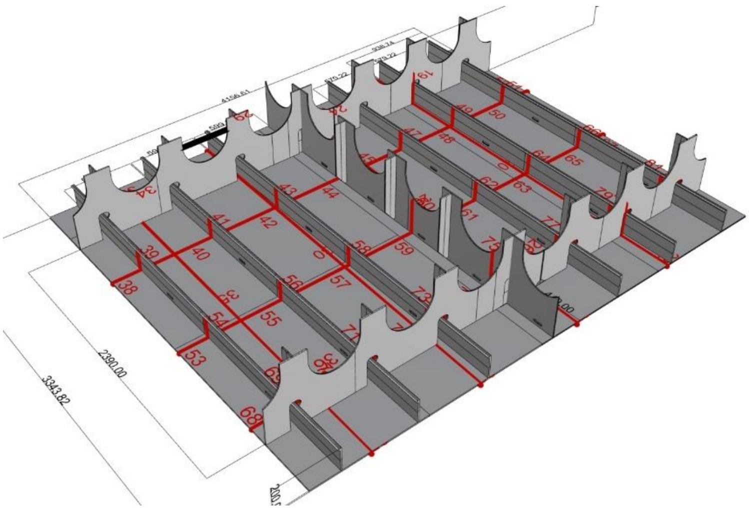
D2.3.1 Cut lines











D2.3.2 Cutting lengths, times and ARENA inputs

Cut line #	Length	Unit	Cut line #	Length	Unit
Cut line 1	300	mm	Cut line 45	590	mm
Cut line 2	300	mm	Cut line 46	200	mm
Cut line 3	300	mm	Cut line 47	590	mm
Cut line 4	400	mm	Cut line 48	200	mm
Cut line 5	300	mm	Cut line 49	600	mm
Cut line 6	300	mm	Cut line 50	200	mm
Cut line 7	300	mm	Cut line 51	600	mm
Cut line 8	300	mm	Cut line 52	200	mm
Cut line 9	300	mm	Cut line 53	590	mm
Cut line 10	300	mm	Cut line 54	200	mm
Cut line 11	400	mm	Cut line 55	590	mm
Cut line 12	300	mm	Cut line 56	200	mm
Cut line 13	300	mm	Cut line 57	300	mm
Cut line 14	300	mm	Cut line 58	232	mm
Cut line 15	300	mm	Cut line 59	200	mm
Cut line 16	300	mm	Cut line 60	590	mm
Cut line 17	300	mm	Cut line 61	200	mm
Cut line 18	497	mm	Cut line 62	590	mm
Cut line 19	300	mm	Cut line 63	200	mm
Cut line 20	2390	mm	Cut line 64	600	mm
Cut line 21	300	mm	Cut line 65	200	mm
Cut line 22	440	mm	Cut line 66	600	mm
Cut line 23	497	mm	Cut line 67	200	mm
Cut line 24	300	mm	Cut line 68	590	mm
Cut line 25	2390	mm	Cut line 69	200	mm
Cut line 26	300	mm	Cut line 70	590	mm
Cut line 27	440	mm	Cut line 71	200	mm
Cut line 28	232	mm	Cut line 72	300	mm
Cut line 29	200	mm	Cut line 73	232	mm
Cut line 30	590	mm	Cut line 74	200	mm
Cut line 31	200	mm	Cut line 75	590	mm
Cut line 32	590	mm	Cut line 76	200	mm
Cut line 33	200	mm	Cut line 77	590	mm
Cut line 34	600	mm	Cut line 78	200	mm
Cut line 35	200	mm	Cut line 79	600	mm
Cut line 36	600	mm	Cut line 80	200	mm
Cut line 37	200	mm	Cut line 81	600	mm
Cut line 38	590	mm	Cut line 82	200	mm
Cut line 39	200	mm	Cut line 83	590	mm
Cut line 40	590	mm	Cut line 84	200	mm
Cut line 41	200	mm	Cut line 85	590	mm
Cut line 42	300	mm	Cut line 86	200	mm
Cut line 43	232	mm	Cut line 87	300	mm
Cut line 44	200	mm			

D2.3.3 ARENA Model for Oxyfuel and Plasma Cutting

D2.3.3.1 Surface Cleaning submodel

Seize

Name	Allocation	Priority	Queue Type	Queue Name	Type	Resource name	Units to seize
Seize	Other	Medium (2)	Queue	Seize.Queue	Seize Set.Queue	Cutting team	1
						Waterjet sc	1

Delay

Name	Allocation	Delay Time	Units
R1	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R3	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R4	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R5	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
R6	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds

Process

Name	Type	Action	Priority	Delay Type	Unit	Allocation	Value
Clean bottom plate	Standard	Delay	Medium	Constant	Seconds	Value Added	4631.169
Clean top plate	Standard	Delay	Medium	Constant	Seconds	Value Added	4631.169
Clean stiffeners	Standard	Delay	Medium	Constant	Seconds	Value Added	411
Clean stringers	Standard	Delay	Medium	Constant	Seconds	Value Added	5348.8
Clean longitudinal frames	Standard	Delay	Medium	Constant	Seconds	Value Added	4851.982
Clean transverse frames	Standard	Delay	Medium	Constant	Seconds	Value Added	1900.776
Prepare machinery	Standard	Delay	Medium	Triangular	Minutes	Value Added	TRIA (5,10,15)

Release

Name	Type	Resource Name	Units to release
Release resources	Resource	Cutting team	1
	Resource	Waterjet sc	1

Calculation of the area for surface treatment

Bottom Plate
Beam : 3343 mm: 3.343 m
Length : 4156 mm: 4.156 m
Thickness : 10 mm: 0.01 m
Area : 13.89351 m2
Volume : 0.138935 m3

Top Plate
Beam : 3343 mm: 3.343 m
Length : 4156 mm: 4.156 m
Thickness : 10 mm: 0.01 m
Area : 13.89351 m2
Volume : 0.138935 m3

Stiffeners
Height : 100 mm: 0.1 m
Length : 822 mm: 0.822 m
Thickness : 10 mm: 0.01 m
Area : 0.0822 m2
Volume : 0.000822 m3
total area :1.233 m2

Stringers
Length : 3343 mm: 3.343 m
Height : 200 mm: 0.2 m
Thickness : 10 mm: 0.01 m
Area : 0.6686 m2 (Single sided)
Volume : 0.006686 m3 (volume of one stringer)
Total area : 8.0232 m2
Total volume : 0.040116 m3

Longitudinal frames
Length : 4156 mm: 4.156 m
Height : 1222 mm: 1.222 m
Thickness : 10 mm: 0.01 m
Total Area : 7.277974 m2

Transverse frames
Length : 3343 mm: 3.343 m
Height : 1222 mm: 1.222 m
Thickness : 10 mm: 0.01 m
area : 4.085146

D2.3.3.2 Cutting in Secondary Cutting Zone submodel

D2.3.3.2.1 Oxyfuel

Seize

Name	Allocation	Priority	Queue Type	Queue Name	Type	Resource name	Units to seize
Seize 1	Other	Medium(2)	Queue	Seize 1.Queue	Seize 1 Set.Queue	Cutting team	1
						Torch	1
Seize 2	Other	Medium(2)	Queue	Seize 2.Queue	Seize 2 Set.Queue	Cutting team	1
						Torch	1

Delay

Name	Allocation	Delay Time	Units	Name	Allocation	Delay Time	Units
Ignition	Other	TRIA (10,15,20)	Seconds	Repos 75	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 1	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 76	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 77	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 3	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 78	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 4	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 79	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 5	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 80	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds

Repos 6	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 81	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 7	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 82	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 8	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 19.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 9	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 20.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 10	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 21.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 11	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 22.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 12	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 23.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 13	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 24.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 14	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 25.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 15	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 26.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 16	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 27.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 17	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 28.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 18	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 29.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 19	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 30.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 20	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 31.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 21	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 32.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 22	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 33.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 23	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 34.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 24	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 35.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 25	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 36.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 26	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 37.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 27	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 38.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 28	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 39.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 29	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 40.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds

Repos 30	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 41.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 31	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 42.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 32	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 43.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 33	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 44.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 34	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 45.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 35	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 46.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 36	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 47.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 37	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 48.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 38	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 49.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 39	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 50.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 40	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 51.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 41	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 52.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 42	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 53.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 43	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 54.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 44	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 55.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 45	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 18.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 46	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 56.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 47	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 57.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 48	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 58.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 49	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 59.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 50	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 60.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 51	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 61.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 52	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 62.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 53	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 63.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds

Repos 54	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 64.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 55	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 65.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 56	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 66.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 57	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 67.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 58	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 68.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 59	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 69.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 60	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 70.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 61	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 71.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 62	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 72.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 63	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 73.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 64	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 74.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 65	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 75.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 66	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 76.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 67	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 77.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 68	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 78.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 69	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 79.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 70	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 80.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 71	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 81.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 72	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Repos 82.2	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds
Repos 73	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds	Separate	Other	2	Minutes
Repos 74	Other	1.5 + 44 * BETA(0.478, 1.19)	Seconds				

Process

Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Cutline 1	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30	Cut line 75	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118
Cutline 2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30	Cut line 76	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20

Cutline 3	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cutline 4	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cutline 5	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cutline 6	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cutline 7	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 8	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 9	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 10	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 11	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 12	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 13	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 14	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 15	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 16	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 17	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 18	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 49.7
Cut line 19	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 20	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 239
Cut line 21	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 22	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 44
Cut line 23	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 49.7
Cut line 24	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 25	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 239
Cut line 26	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 27	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 44
Cut line 28	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 23.2
Cut line 29	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 30	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 31	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 32	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 33	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 34	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 35	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 36	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 37	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 38	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59

Cut line 77	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118
Cut line 78	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 79	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 80	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 81	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 82	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 18.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 49.7
Cut line 19.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 20.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 239
Cut line 21.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 22.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 44
Cut line 23.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 49.7
Cut line 24.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 25.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 239
Cut line 26.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 60
Cut line 27.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 44
Cut line 28.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 23.2
Cut line 29.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 30.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 31.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 32.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 33.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 34.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 35.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 36.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 37.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 38.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 39.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 40.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 41.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 42.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 43.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 46.4
Cut line 44.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 45.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118
Cut line 46.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 47.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118

Cut line 39	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 48.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 40	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59	Cut line 49.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 41	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 50.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 42	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30	Cut line 51.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 43	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 46.4	Cut line 52.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 44	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 53.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 45	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118	Cut line 54.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 46	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 55.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 47	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118	Cut line 56.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 48	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 57.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 49	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120	Cut line 58.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 46.4
Cut line 50	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 59.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 51	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120	Cut line 60.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118
Cut line 52	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 61.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 53	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59	Cut line 62.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118
Cut line 54	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 63.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 55	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59	Cut line 64.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 56	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 65.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 57	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30	Cut line 66.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 58	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 46.4	Cut line 67.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 59	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 68.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 60	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118	Cut line 69.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 61	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 70.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59
Cut line 62	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118	Cut line 71.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40
Cut line 63	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 72.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30
Cut line 64	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120	Cut line 73.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 46.4
Cut line 65	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 74.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 66	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120	Cut line 75.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118
Cut line 67	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20	Cut line 76.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 68	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59	Cut line 77.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 118
Cut line 69	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 78.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 70	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 59	Cut line 79.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 71	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 40	Cut line 80.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 72	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 30	Cut line 81.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 120
Cut line 73	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 46.4	Cut line 82.2	Delay	Expression	8.5 + 8 * BETA(0.978, 1.1) + 20
Cut line 74	Delay	Expression					

Release

Name	Type	Resource Name	Units to release
Release 1	Resource	Cutting team	1
	Resource	Torch	1
Release 2	Resource	Cutting team	1
	Resource	Torch	1

D2.3.3.2.2 Plasma – Hypermax 85

Process

Name	Action	Delay Type	Value	Name	Type	Action	Delay Type	Value
Cutline 1	Delay	Constant	18.82	Cut line 75	Standard	Delay	Constant	71.1
Cutline 2	Delay	Constant	18.82	Cut line 76	Standard	Delay	Constant	12.88
Cutline 3	Delay	Constant	18.82	Cut line 77	Standard	Delay	Constant	71.1
Cutline 4	Delay	Constant	24.76	Cut line 78	Standard	Delay	Constant	12.88
Cutline 5	Delay	Constant	18.82	Cut line 79	Standard	Delay	Constant	72.29
Cutline 6	Delay	Constant	18.82	Cut line 80	Standard	Delay	Constant	12.88
Cutline 7	Delay	Constant	18.82	Cut line 81	Standard	Delay	Constant	72.29
Cut line 8	Delay	Constant	18.82	Cut line 82	Standard	Delay	Constant	12.88
Cut line 9	Delay	Constant	18.82	Cut line 18.2	Standard	Delay	Constant	30.52
Cut line 10	Delay	Constant	18.82	Cut line 19.2	Standard	Delay	Constant	36.64
Cut line 11	Delay	Constant	24.76	Cut line 20.2	Standard	Delay	Constant	142.98
Cut line 12	Delay	Constant	18.82	Cut line 21.2	Standard	Delay	Constant	36.64
Cut line 13	Delay	Constant	18.82	Cut line 22.2	Standard	Delay	Constant	27.14
Cut line 14	Delay	Constant	18.82	Cut line 23.2	Standard	Delay	Constant	30.52
Cut line 15	Delay	Constant	18.82	Cut line 24.2	Standard	Delay	Constant	36.64
Cut line 16	Delay	Constant	18.82	Cut line 25.2	Standard	Delay	Constant	142.98
Cut line 17	Delay	Constant	18.82	Cut line 26.2	Standard	Delay	Constant	36.64
Cut line 18	Delay	Constant	30.52	Cut line 27.2	Standard	Delay	Constant	27.14
Cut line 19	Delay	Constant	36.64	Cut line 28.2	Standard	Delay	Constant	14.78
Cut line 20	Delay	Constant	142.98	Cut line 29.2	Standard	Delay	Constant	24.76
Cut line 21	Delay	Constant	36.64	Cut line 30.2	Standard	Delay	Constant	36.05
Cut line 22	Delay	Constant	27.14	Cut line 31.2	Standard	Delay	Constant	24.76
Cut line 23	Delay	Constant	30.52	Cut line 32.2	Standard	Delay	Constant	36.05
Cut line 24	Delay	Constant	36.64	Cut line 33.2	Standard	Delay	Constant	12.88
Cut line 25	Delay	Constant	142.98	Cut line 34.2	Standard	Delay	Constant	72.29
Cut line 26	Delay	Constant	36.64	Cut line 35.2	Standard	Delay	Constant	12.88
Cut line 27	Delay	Constant	27.14	Cut line 36.2	Standard	Delay	Constant	72.29
Cut line 28	Delay	Constant	14.78	Cut line 37.2	Standard	Delay	Constant	12.88
Cut line 29	Delay	Constant	24.76	Cut line 38.2	Standard	Delay	Constant	36.05
Cut line 30	Delay	Constant	36.05	Cut line 39.2	Standard	Delay	Constant	24.76
Cut line 31	Delay	Constant	24.76	Cut line 40.2	Standard	Delay	Constant	36.05
Cut line 32	Delay	Constant	36.05	Cut line 41.2	Standard	Delay	Constant	24.76

Cut line 33	Delay	Constant	12.88	Cut line 42.2	Standard	Delay	Constant	18.82
Cut line 34	Delay	Constant	72.29	Cut line 43.2	Standard	Delay	Constant	28.56
Cut line 35	Delay	Constant	12.88	Cut line 44.2	Standard	Delay	Constant	12.88
Cut line 36	Delay	Constant	72.29	Cut line 45.2	Standard	Delay	Constant	71.1
Cut line 37	Delay	Constant	12.88	Cut line 46.2	Standard	Delay	Constant	12.88
Cut line 38	Delay	Constant	36.05	Cut line 47.2	Standard	Delay	Constant	71.1
Cut line 39	Delay	Constant	24.76	Cut line 48.2	Standard	Delay	Constant	12.88
Cut line 40	Delay	Constant	36.05	Cut line 49.2	Standard	Delay	Constant	72.29
Cut line 41	Delay	Constant	24.76	Cut line 50.2	Standard	Delay	Constant	12.88
Cut line 42	Delay	Constant	18.82	Cut line 51.2	Standard	Delay	Constant	72.29
Cut line 43	Delay	Constant	28.56	Cut line 52.2	Standard	Delay	Constant	12.88
Cut line 44	Delay	Constant	12.88	Cut line 53.2	Standard	Delay	Constant	36.05
Cut line 45	Delay	Constant	71.1	Cut line 54.2	Standard	Delay	Constant	24.76
Cut line 46	Delay	Constant	12.88	Cut line 55.2	Standard	Delay	Constant	36.05
Cut line 47	Delay	Constant	71.1	Cut line 56.2	Standard	Delay	Constant	24.76
Cut line 48	Delay	Constant	12.88	Cut line 57.2	Standard	Delay	Constant	18.82
Cut line 49	Delay	Constant	72.29	Cut line 58.2	Standard	Delay	Constant	28.56
Cut line 50	Delay	Constant	12.88	Cut line 59.2	Standard	Delay	Constant	12.88
Cut line 51	Delay	Constant	72.29	Cut line 60.2	Standard	Delay	Constant	71.1
Cut line 52	Delay	Constant	12.88	Cut line 61.2	Standard	Delay	Constant	12.88
Cut line 53	Delay	Constant	36.05	Cut line 62.2	Standard	Delay	Constant	71.1
Cut line 54	Delay	Constant	24.76	Cut line 63.2	Standard	Delay	Constant	12.88
Cut line 55	Delay	Constant	36.05	Cut line 64.2	Standard	Delay	Constant	72.29
Cut line 56	Delay	Constant	24.76	Cut line 65.2	Standard	Delay	Constant	12.88
Cut line 57	Delay	Constant	18.82	Cut line 66.2	Standard	Delay	Constant	72.29
Cut line 58	Delay	Constant	28.56	Cut line 67.2	Standard	Delay	Constant	12.88
Cut line 59	Delay	Constant	12.88	Cut line 68.2	Standard	Delay	Constant	36.05
Cut line 60	Delay	Constant	71.1	Cut line 69.2	Standard	Delay	Constant	24.76
Cut line 61	Delay	Constant	12.88	Cut line 70.2	Standard	Delay	Constant	36.05
Cut line 62	Delay	Constant	71.1	Cut line 71.2	Standard	Delay	Constant	24.76
Cut line 63	Delay	Constant	12.88	Cut line 72.2	Standard	Delay	Constant	18.82
Cut line 64	Delay	Constant	72.29	Cut line 73.2	Standard	Delay	Constant	28.56
Cut line 65	Delay	Constant	12.88	Cut line 74.2	Standard	Delay	Constant	12.88
Cut line 66	Delay	Constant	72.29	Cut line 75.2	Standard	Delay	Constant	71.1
Cut line 67	Delay	Constant	12.88	Cut line 76.2	Standard	Delay	Constant	12.88
Cut line 68	Delay	Constant	36.05	Cut line 77.2	Standard	Delay	Constant	71.1
Cut line 69	Delay	Constant	24.76	Cut line 78.2	Standard	Delay	Constant	12.88
Cut line 70	Delay	Constant	36.05	Cut line 79.2	Standard	Delay	Constant	72.29
Cut line 71	Delay	Constant	24.76	Cut line 80.2	Standard	Delay	Constant	12.88
Cut line 72	Delay	Constant	18.82	Cut line 81.2	Standard	Delay	Constant	72.29
Cut line 73	Delay	Constant	28.56	Cut line 82.2	Standard	Delay	Constant	12.88
Cut line 74	Delay	Constant	12.88					

D2.3.3.2.3 Plasma – Hypermax 125

Process

Name	Action	Delay Type	Value	Name	Type	Action	Delay Type	Value
Cutline 1	Delay	Constant	10.89	Cut line 75	Standard	Delay	Constant	39.9
Cutline 2	Delay	Constant	10.89	Cut line 76	Standard	Delay	Constant	7.59
Cutline 3	Delay	Constant	10.89	Cut line 77	Standard	Delay	Constant	39.9
Cutline 4	Delay	Constant	14.19	Cut line 78	Standard	Delay	Constant	7.59
Cutline 5	Delay	Constant	10.89	Cut line 79	Standard	Delay	Constant	40.56
Cutline 6	Delay	Constant	10.89	Cut line 80	Standard	Delay	Constant	7.59
Cutline 7	Delay	Constant	10.89	Cut line 81	Standard	Delay	Constant	40.56
Cut line 8	Delay	Constant	10.89	Cut line 82	Standard	Delay	Constant	7.59
Cut line 9	Delay	Constant	10.89	Cut line 18.2	Standard	Delay	Constant	17.38
Cut line 10	Delay	Constant	10.89	Cut line 19.2	Standard	Delay	Constant	20.78
Cut line 11	Delay	Constant	14.19	Cut line 20.2	Standard	Delay	Constant	79.79
Cut line 12	Delay	Constant	10.89	Cut line 21.2	Standard	Delay	Constant	20.78
Cut line 13	Delay	Constant	10.89	Cut line 22.2	Standard	Delay	Constant	15.51
Cut line 14	Delay	Constant	10.89	Cut line 23.2	Standard	Delay	Constant	17.38
Cut line 15	Delay	Constant	10.89	Cut line 24.2	Standard	Delay	Constant	20.78
Cut line 16	Delay	Constant	10.89	Cut line 25.2	Standard	Delay	Constant	79.79
Cut line 17	Delay	Constant	10.89	Cut line 26.2	Standard	Delay	Constant	20.78
Cut line 18	Delay	Constant	17.38	Cut line 27.2	Standard	Delay	Constant	15.51
Cut line 19	Delay	Constant	20.78	Cut line 28.2	Standard	Delay	Constant	8.65
Cut line 20	Delay	Constant	79.79	Cut line 29.2	Standard	Delay	Constant	14.19
Cut line 21	Delay	Constant	20.78	Cut line 30.2	Standard	Delay	Constant	20.45
Cut line 22	Delay	Constant	15.51	Cut line 31.2	Standard	Delay	Constant	14.19
Cut line 23	Delay	Constant	17.38	Cut line 32.2	Standard	Delay	Constant	20.45
Cut line 24	Delay	Constant	20.78	Cut line 33.2	Standard	Delay	Constant	7.59
Cut line 25	Delay	Constant	79.79	Cut line 34.2	Standard	Delay	Constant	40.56
Cut line 26	Delay	Constant	20.78	Cut line 35.2	Standard	Delay	Constant	7.59
Cut line 27	Delay	Constant	15.51	Cut line 36.2	Standard	Delay	Constant	40.56
Cut line 28	Delay	Constant	8.65	Cut line 37.2	Standard	Delay	Constant	7.59
Cut line 29	Delay	Constant	14.19	Cut line 38.2	Standard	Delay	Constant	20.45
Cut line 30	Delay	Constant	20.45	Cut line 39.2	Standard	Delay	Constant	14.19
Cut line 31	Delay	Constant	14.19	Cut line 40.2	Standard	Delay	Constant	20.45
Cut line 32	Delay	Constant	20.45	Cut line 41.2	Standard	Delay	Constant	14.19
Cut line 33	Delay	Constant	7.59	Cut line 42.2	Standard	Delay	Constant	10.89
Cut line 34	Delay	Constant	40.56	Cut line 43.2	Standard	Delay	Constant	16.3
Cut line 35	Delay	Constant	7.59	Cut line 44.2	Standard	Delay	Constant	7.59
Cut line 36	Delay	Constant	40.56	Cut line 45.2	Standard	Delay	Constant	39.9
Cut line 37	Delay	Constant	7.59	Cut line 46.2	Standard	Delay	Constant	7.59
Cut line 38	Delay	Constant	20.45	Cut line 47.2	Standard	Delay	Constant	39.9
Cut line 39	Delay	Constant	14.19	Cut line 48.2	Standard	Delay	Constant	7.59
Cut line 40	Delay	Constant	20.45	Cut line 49.2	Standard	Delay	Constant	40.56
Cut line 41	Delay	Constant	14.19	Cut line 50.2	Standard	Delay	Constant	7.59
Cut line 42	Delay	Constant	10.89	Cut line 51.2	Standard	Delay	Constant	40.56

Cut line 43	Delay	Constant	16.3	Cut line 52.2	Standard	Delay	Constant	7.59
Cut line 44	Delay	Constant	7.59	Cut line 53.2	Standard	Delay	Constant	20.45
Cut line 45	Delay	Constant	39.9	Cut line 54.2	Standard	Delay	Constant	14.19
Cut line 46	Delay	Constant	7.59	Cut line 55.2	Standard	Delay	Constant	20.45
Cut line 47	Delay	Constant	39.9	Cut line 56.2	Standard	Delay	Constant	14.19
Cut line 48	Delay	Constant	7.59	Cut line 57.2	Standard	Delay	Constant	10.89
Cut line 49	Delay	Constant	40.56	Cut line 58.2	Standard	Delay	Constant	16.3
Cut line 50	Delay	Constant	7.59	Cut line 59.2	Standard	Delay	Constant	7.59
Cut line 51	Delay	Constant	40.56	Cut line 60.2	Standard	Delay	Constant	39.9
Cut line 52	Delay	Constant	7.59	Cut line 61.2	Standard	Delay	Constant	7.59
Cut line 53	Delay	Constant	20.45	Cut line 62.2	Standard	Delay	Constant	39.9
Cut line 54	Delay	Constant	14.19	Cut line 63.2	Standard	Delay	Constant	7.59
Cut line 55	Delay	Constant	20.45	Cut line 64.2	Standard	Delay	Constant	40.56
Cut line 56	Delay	Constant	14.19	Cut line 65.2	Standard	Delay	Constant	7.59
Cut line 57	Delay	Constant	10.89	Cut line 66.2	Standard	Delay	Constant	40.56
Cut line 58	Delay	Constant	16.3	Cut line 67.2	Standard	Delay	Constant	7.59
Cut line 59	Delay	Constant	7.59	Cut line 68.2	Standard	Delay	Constant	20.45
Cut line 60	Delay	Constant	39.9	Cut line 69.2	Standard	Delay	Constant	14.19
Cut line 61	Delay	Constant	7.59	Cut line 70.2	Standard	Delay	Constant	20.45
Cut line 62	Delay	Constant	39.9	Cut line 71.2	Standard	Delay	Constant	14.19
Cut line 63	Delay	Constant	7.59	Cut line 72.2	Standard	Delay	Constant	10.89
Cut line 64	Delay	Constant	40.56	Cut line 73.2	Standard	Delay	Constant	16.3
Cut line 65	Delay	Constant	7.59	Cut line 74.2	Standard	Delay	Constant	7.59
Cut line 66	Delay	Constant	40.56	Cut line 75.2	Standard	Delay	Constant	39.9
Cut line 67	Delay	Constant	7.59	Cut line 76.2	Standard	Delay	Constant	7.59
Cut line 68	Delay	Constant	20.45	Cut line 77.2	Standard	Delay	Constant	39.9
Cut line 69	Delay	Constant	14.19	Cut line 78.2	Standard	Delay	Constant	7.59
Cut line 70	Delay	Constant	20.45	Cut line 79.2	Standard	Delay	Constant	40.56
Cut line 71	Delay	Constant	14.19	Cut line 80.2	Standard	Delay	Constant	7.59
Cut line 72	Delay	Constant	10.89	Cut line 81.2	Standard	Delay	Constant	40.56
Cut line 73	Delay	Constant	16.3	Cut line 82.2	Standard	Delay	Constant	7.59
Cut line 74	Delay	Constant	7.59					

D2.3.3.4 ARENA Model for Waterjet Cutting

Seize

Name	Allocation	Priority	Queue Type	Queue Name	Type	Resource name	Units to seize
Seize 1	Other	Medium(2)	Queue	Seize 1.Queue	Seize 1 Set.Queue	Cutting team	1
						Waterjet cutter	1
Seize 2	Other	Medium(2)	Queue	Seize 2.Queue	Seize 2 Set.Queue	Cutting team	1
						Waterjet cutter	1

Delay

Name	Allocation	Delay Time	Units	Name	Allocation	Delay Time	Units
Separate	Other	2	Minutes	Setup 9	Other	TRIA (10,15,20)	Minutes
Setup 1	Other	TRIA (10,15,20)	Minutes	Setup 10	Other	TRIA (10,15,20)	Minutes
Setup 2	Other	TRIA (10,15,20)	Minutes	Setup 11	Other	TRIA (10,15,20)	Minutes
Setup 3	Other	TRIA (10,15,20)	Minutes	Setup 12	Other	TRIA (10,15,20)	Minutes
Setup 4	Other	TRIA (10,15,20)	Minutes	Setup 13	Other	TRIA (10,15,20)	Minutes
Setup 5	Other	TRIA (10,15,20)	Minutes	Setup 14	Other	TRIA (10,15,20)	Minutes
Setup 6	Other	TRIA (10,15,20)	Minutes	Setup 15	Other	TRIA (10,15,20)	Minutes
Setup 7	Other	TRIA (10,15,20)	Minutes	Setup 16	Other	TRIA (10,15,20)	Minutes
Setup 8	Other	TRIA (10,15,20)	Minutes	Setup 17	Other	TRIA (10,15,20)	Minutes

Process

Name	Action	Delay Type	Value	Name	Action	Delay Type	Value
Cutline 1	Delay	Constant	75.31	Cut line 75	Delay	Constant	148.12
Cutline 2	Delay	Constant	75.31	Cut line 76	Delay	Constant	50.21
Cutline 3	Delay	Constant	75.31	Cut line 77	Delay	Constant	148.12
Cutline 4	Delay	Constant	100.42	Cut line 78	Delay	Constant	50.21
Cutline 5	Delay	Constant	75.31	Cut line 79	Delay	Constant	150.63
Cutline 6	Delay	Constant	75.31	Cut line 80	Delay	Constant	50.21
Cutline 7	Delay	Constant	75.31	Cut line 81	Delay	Constant	150.63
Cut line 8	Delay	Constant	75.31	Cut line 82	Delay	Constant	50.21
Cut line 9	Delay	Constant	75.31	Cut line 18.2	Delay	Constant	124.77
Cut line 10	Delay	Constant	75.31	Cut line 19.2	Delay	Constant	75.31
Cut line 11	Delay	Constant	100.42	Cut line 20.2	Delay	Constant	600
Cut line 12	Delay	Constant	75.31	Cut line 21.2	Delay	Constant	75.31
Cut line 13	Delay	Constant	75.31	Cut line 22.2	Delay	Constant	110.46
Cut line 14	Delay	Constant	75.31	Cut line 23.2	Delay	Constant	124.77
Cut line 15	Delay	Constant	75.31	Cut line 24.2	Delay	Constant	75.31
Cut line 16	Delay	Constant	75.31	Cut line 25.2	Delay	Constant	600
Cut line 17	Delay	Constant	75.31	Cut line 26.2	Delay	Constant	75.31
Cut line 18	Delay	Constant	124.77	Cut line 27.2	Delay	Constant	110.46
Cut line 19	Delay	Constant	75.31	Cut line 28.2	Delay	Constant	58.24
Cut line 20	Delay	Constant	600	Cut line 29.2	Delay	Constant	50.21
Cut line 21	Delay	Constant	75.31	Cut line 30.2	Delay	Constant	148.12
Cut line 22	Delay	Constant	110.46	Cut line 31.2	Delay	Constant	50.21
Cut line 23	Delay	Constant	124.77	Cut line 32.2	Delay	Constant	148.12
Cut line 24	Delay	Constant	75.31	Cut line 33.2	Delay	Constant	50.21
Cut line 25	Delay	Constant	600	Cut line 34.2	Delay	Constant	150.63
Cut line 26	Delay	Constant	75.31	Cut line 35.2	Delay	Constant	50.21
Cut line 27	Delay	Constant	110.46	Cut line 36.2	Delay	Constant	150.63
Cut line 28	Delay	Constant	58.24	Cut line 37.2	Delay	Constant	50.21
Cut line 29	Delay	Constant	50.21	Cut line 38.2	Delay	Constant	148.12
Cut line 30	Delay	Constant	148.12	Cut line 39.2	Delay	Constant	50.21

Cut line 31	Delay	Constant	50.21	Cut line 40.2	Delay	Constant	148.12
Cut line 32	Delay	Constant	148.12	Cut line 41.2	Delay	Constant	50.21
Cut line 33	Delay	Constant	50.21	Cut line 42.2	Delay	Constant	75.31
Cut line 34	Delay	Constant	150.63	Cut line 43.2	Delay	Constant	58.24
Cut line 35	Delay	Constant	50.21	Cut line 44.2	Delay	Constant	50.21
Cut line 36	Delay	Constant	150.63	Cut line 45.2	Delay	Constant	148.12
Cut line 37	Delay	Constant	50.21	Cut line 46.2	Delay	Constant	50.21
Cut line 38	Delay	Constant	148.12	Cut line 47.2	Delay	Constant	148.12
Cut line 39	Delay	Constant	50.21	Cut line 48.2	Delay	Constant	50.21
Cut line 40	Delay	Constant	148.12	Cut line 49.2	Delay	Constant	150.63
Cut line 41	Delay	Constant	50.21	Cut line 50.2	Delay	Constant	50.21
Cut line 42	Delay	Constant	75.31	Cut line 51.2	Delay	Constant	150.63
Cut line 43	Delay	Constant	58.24	Cut line 52.2	Delay	Constant	50.21
Cut line 44	Delay	Constant	50.21	Cut line 53.2	Delay	Constant	148.12
Cut line 45	Delay	Constant	148.12	Cut line 54.2	Delay	Constant	50.21
Cut line 46	Delay	Constant	50.21	Cut line 55.2	Delay	Constant	148.12
Cut line 47	Delay	Constant	148.12	Cut line 56.2	Delay	Constant	50.21
Cut line 48	Delay	Constant	50.21	Cut line 57.2	Delay	Constant	75.31
Cut line 49	Delay	Constant	150.63	Cut line 58.2	Delay	Constant	58.24
Cut line 50	Delay	Constant	50.21	Cut line 59.2	Delay	Constant	50.21
Cut line 51	Delay	Constant	150.63	Cut line 60.2	Delay	Constant	148.12
Cut line 52	Delay	Constant	50.21	Cut line 61.2	Delay	Constant	50.21
Cut line 53	Delay	Constant	148.12	Cut line 62.2	Delay	Constant	148.12
Cut line 54	Delay	Constant	50.21	Cut line 63.2	Delay	Constant	50.21
Cut line 55	Delay	Constant	148.12	Cut line 64.2	Delay	Constant	150.63
Cut line 56	Delay	Constant	50.21	Cut line 65.2	Delay	Constant	50.21
Cut line 57	Delay	Constant	75.31	Cut line 66.2	Delay	Constant	150.63
Cut line 58	Delay	Constant	58.24	Cut line 67.2	Delay	Constant	50.21
Cut line 59	Delay	Constant	50.21	Cut line 68.2	Delay	Constant	148.12
Cut line 60	Delay	Constant	148.12	Cut line 69.2	Delay	Constant	50.21
Cut line 61	Delay	Constant	50.21	Cut line 70.2	Delay	Constant	148.12
Cut line 62	Delay	Constant	148.12	Cut line 71.2	Delay	Constant	50.21
Cut line 63	Delay	Constant	50.21	Cut line 72.2	Delay	Constant	75.31
Cut line 64	Delay	Constant	150.63	Cut line 73.2	Delay	Constant	58.24
Cut line 65	Delay	Constant	50.21	Cut line 74.2	Delay	Constant	50.21
Cut line 66	Delay	Constant	150.63	Cut line 75.2	Delay	Constant	148.12
Cut line 67	Delay	Constant	50.21	Cut line 76.2	Delay	Constant	50.21
Cut line 68	Delay	Constant	148.12	Cut line 77.2	Delay	Constant	148.12
Cut line 69	Delay	Constant	50.21	Cut line 78.2	Delay	Constant	50.21
Cut line 70	Delay	Constant	148.12	Cut line 79.2	Delay	Constant	150.63
Cut line 71	Delay	Constant	50.21	Cut line 80.2	Delay	Constant	50.21
Cut line 72	Delay	Constant	75.31	Cut line 81.2	Delay	Constant	150.63
Cut line 73	Delay	Constant	58.24	Cut line 82.2	Delay	Constant	50.21
Cut line 74	Delay	Constant	50.21				

D.3. Structured interview Data collection

Following template was followed to collect the data in a structured manner. After this face-to-face interview, numerous phone interviews were also conducted as data needs or requirements raise.

Yard and resource plan		
Yearly dismantling capacity of the new yard:		
Yearly dismantling capacity goal for the long term:		
Dimensions of the facility:		
Target ships for the new yard:		
Facilities planned for the new yard:		
Current offer price for the ships per LDT:		
Current price from the steel mill per LDT		
Average profit per LDT in the current yard		
Cost categories in the yard and distribution of these costs with regards to total dismantling cost of an average ship		
Income sources from the ship, distribution of these income sources with regards to total income for an average ship		
Details of crane (capacity, number, brand, hourly cost):		
Details of polygrab (capacity, number, brand, hourly cost):		
Types of employee planned:		
No of employee for each category:		
Cost for each employee category:		
Process data		
Total duration and types of surveys on board the ship, who is involved?		
Type of fuel in Oxy-fuel cutting:		
Details of the oxy-fuel torch (brand, model)		
Hourly oxygen and fuel consumption:		
Cost of other consumables		
Size of the plates cut:		
Average amount of produced steel per day:		
Duration of	the IHM survey take and the cost?	
	getting the approvals from regulators once you submitted all the necessary documents?	
	setting the security measures before starting cutting?	
	removing the navigational equipment?	
	removing the loose items on board the ship?	
	removing the cables and electronics?	
	removing the pipes and connections?	
	loading an average piece to crane (hooking up and doing the connections)	
	transferring an average piece to secondary zone?	
Subcontracting costs		
IHM Survey cost		
Hazmat removal and landfill cost		
Tugboat cost		
Approval and certification cost		
Customs tax and other associated cost		
Cost of overheads (electricity, maintenance, keeping etc.)		
Cost of training		
Cost of maintenance		
Cost of PPE		
Cost of transport to steel mill		

Appendix E: Analysis of Strengths and Weaknesses of the Selected Cutting Technologies

Three different cutting methods will be tested in this study using simulation. As a next step, different cutting methods that can apply to the ship recycling industry were investigated, and the required data was collected. Summary of the applicable cutting methods and collected data can be found in this section.

Oxy-fuel Cutting

Oxy-fuel cutting is the most widely applied cutting method in the ship recycling industry. The initial investment and maintenance costs of the equipment are low, the system is portable, and the cut range is extensive; oxy-fuel torches can cut thicknesses from 0.5 mm to 250mm (TWI-Global, 2011). Furthermore, oxy-fuel cutting does not require expert skills; moderate skills are enough to operate oxy-fuel torches.

In order to find alternatives to the oxy-fuel cutting process, it is essential to understand the process of oxy-fuel cutting, or also known as, “torch cutting”. The process of the oxy-fuel cutting has three main steps; heating, piercing and cutting. Before starting the cutting, the steel needs to be preheated to the ignition temperature(ESAB, 2013a). The ignition temperature is different for every material/alloy, e.g. 700°C - 900°C for steel (TWI-Global, 2011). Once the ignition temperature of the steel is reached, steel loses its protective properties (HGG, n.d.) and a jet of pure oxygen is directed to a heated zone. This starts the rapid oxidation process (TWI-Global, 2011, ESAB, 2013a) and creates the “slag” which has a lower melting point than the steel (HGG, n.d.). Oxygen jet then blows the slag away (piercing) and once the steel is pierced, the continuous cut can be formed by moving the torch at a constant speed through the steel (cutting).

In production focused industries quality of the cut is very important. However, in the ship recycling, quality of the cut is not necessary as the steel will end up in the steel mill and furnace. For the ship recycling industry cutting speed is an essential factor. Cutting speed will affect two factors; productivity in the primary and secondary cutting zones and labour costs. The cutting speed is dependent on two main factors; choice of fuel gas, purity of oxygen and type of the equipment (torch, nozzle).

In the ship recycling industry acetylene, propane and natural gas are used commonly as fuels. Natural gas and propane have lower flame temperatures compared to the maximum flame temperature of acetylene as fuel gas. This causes more extended heating and piercing times, but overall the speed of the process is almost the same with each gas.

Oxy-fuel cutting Equipment is highly portable, which is an essential requirement for the ship recycling yard operations. The oxy-fuel cutting-kit comprises of oxygen and fuel bottles, pressure regulators, flashback arresters (not commonly used in South Asia yards), torch itself and cutting nozzle (Weldability, 2007).

As mentioned before, oxy-fuel cutting is cheap, simple and easy to use method. Advantages and disadvantages of the oxy-fuel cutting are summarised below;

Advantages

+ The initial, maintenance and consumable costs of the equipment is low
+ Can be used with different fuels
+ Portable to use in the field
+ Can be used to cut thick steels
+ Can be used both in manual and mechanised operations
+ Mild and low alloy steels
+ A wide range of thickness (1 mm to 1000 mm)

Disadvantages

- Sometimes surface preparation is required for occupational and environmental safety
- Not very suitable for stainless steels and aluminium
- HSE problems especially risk of fire and explosions

Currently, oxy-LPG cutting is being used in the case study yard, and timings for a typical block dismantling operation were recorded which will be summarised in section 7.7. Also, cutting times for different plate thicknesses were taken in from the manufacturer's manual (Praxair, 2012).

Plasma Cutting

Plasma cutting is an innovative cutting method that is becoming increasingly popular, and it is a powerful alternative process for cutting steel and other metals. Plasma cutting uses an electrical arch through a jet of oxygen or inert gas to melt and expel material from the cut (TWI-Global, 2017b). The basic patent on plasma arc cutting (PAC) was applied for by Gage in 1955, and In its original version, PAC was used primarily for cutting stainless steel and aluminium (Nemchinsky and Severance, 2006). Since then, plasma cutting has come a long way.

Plasma is the fourth state of matter (Nemchinsky and Severance, 2006). A plasma cutter uses the electrically conductive gas which is in the plasma state to transfer energy from a power supply to any conductive material (LE, 2017). Plasma cutting process consists of metal melting and then blowing the cut metal away from the material (Nemchinsky and Severance, 2006).

The first step of the plasma cutting is sending an electric arc through the gas. As the metal being cut is part of the circuit, the electrical conductivity of the plasma causes the arc to transfer to the metal or "workpiece" (Torchmate, 2017). This high-pressure gas and an electric arc are commonly referred as "plasma jet", and it immediately reaches temperatures up to 40000 ˚F (LE, 2017), and pierces through the metal and blows the molten material away. The most common gas that is used in plasma cutting is air. In high-power devices argon, nitrogen, hydrogen and carbon dioxide are also being used.

Plasma cutting offers much higher speeds compared to traditional oxy-fuel cutting (ESAB, 2013b). In addition to the speed, plasma has the advantage of being capable of processing a variety of electrically conducting materials such as Stainless steel, manganese, titanium alloys, copper, magnesium, aluminium and its alloys and cast iron (Salonitis and Vatousianos, 2012). This may be especially advantageous for certain ship types (e.g. LNG carriers) in which stainless steel and non-ferrous metals have been heavily used. Equipment for plasma cutting was expensive in the past, but new plasma cutters are becoming cheaper. The quality of the plasma cut edge is similar to that achieved with the oxy-fuel process (TWI-Global, 2017b). Advantages of the plasma cutting are summarised below (Compiled from TWI-Global (2017b), Kjellberg (n.d.));

Advantages;

+ Lowest requirements on working environment, thus very appropriate for ship recycling yards
+ Compared to oxy-fuel, the cutting speed is up to 10 times higher when cutting thin and medium-sized plates (up to 10 times higher compared to oxy-fuel)
+ One or more torches can be connected to a single supply
+ Can cut thick steels
+ Cuts high carbon and stainless steel
+ Cutting of high-tensile mild steel with low heat input
+ Consumable gas costs are low
+ It can cut a very wide range of materials (e.g. stainless steel and aluminium)
+ Occupational hazards related to plasma cuttings are less compared to oxyfuel cutting
+ Low consumable (air) costs
+ Low fume when cutting underwater

Disadvantages

- Creates noise problems while cutting thick sections
- Emission problem due to cutting fumes
- Arc glare when cutting in air
- Consumables (electrode and nozzle) costs

Waterjet cutting

Water jet cutting is a type of cold cutting process, and it is one of the widely used cutting methods (Keyur D. Desai et al., 2017). In principle, the waterjet machine uses a stream of water with high pressure to cut through a material using erosion (Wang and Wong, 1999). It is possible to increase the cutting power in order to cut the thicker or stronger materials by adding an abrasive to the waterjet (OMAX, 2017b). Waterjet prototype was first presented in 1968 by Norman Franz (Hashish, 1984) but the development of high-pressure abrasive water jet cut technology has started in the 1980s (Birtu and Avramescu, 2012).

The operating principle of abrasive waterjets can be described as follows; pressurising and forcing water through a tiny hole which is often mixed with garnet abrasive (ICEE, n.d.). Moreover, these abrasive particles are accelerated through mixing them with a jet of water (driven by pressures of up to 45,000 psi). This water-abrasive mixing and acceleration of particles process take place in a mixing chamber made of a hard material such as tungsten carbide or boron carbide (Hashish, 1984).

Waterjets can be investigated in two main categories;

- Pure-water waterjet

This type of waterjet machines uses as the separating tool. Using this method, soft engineering materials such as paper, wood, textile, food, plastics, sealing materials can be cut (bystronic.com, 2017, Alsoufi, 2017).

- Abrasive waterjet

Abrasive waterjet procedure uses the abrasive particles and mixes them with a jet of water. Then this mixture is used as the separating device (bystronic.com, 2017). Abrasive waterjet cutting is suitable to work with hard engineering materials; from marble to steel.

The water jet is currently applied in many different industries; automotive, aerospace, construction engineering, or repair and upgrade of the chemical plants, oil and gas, offshore industries and sometimes cutting of munition s due to the advantage of the very low risk of fire cold cutting provides (Berglund, 2006). For example, the waterjet cutting provider Aquablast (2017) applied waterjet cutting to a collapsed oil storage tank near Athens. The tank had to be cut into manageable sections in order to lift by a crane, but the crude oil residues in the bottom of the tank made it very dangerous to use thermal cutting methods. Aquablast used a mobile abrasive jet to conduct cutting operation on 6 mm buckled plates at an average cutting rate of 7 meters per hour (Aquablast, 2017).

Similarly, during ship recycling there are areas of the ship that is dangerous to apply thermal cutting methods; e.g. Oil and fuel tanks, double bottom, pipes and so forth. Therefore, waterjet cutting can be used in the area of ship recycling to cut any area with fire/explosion risk.

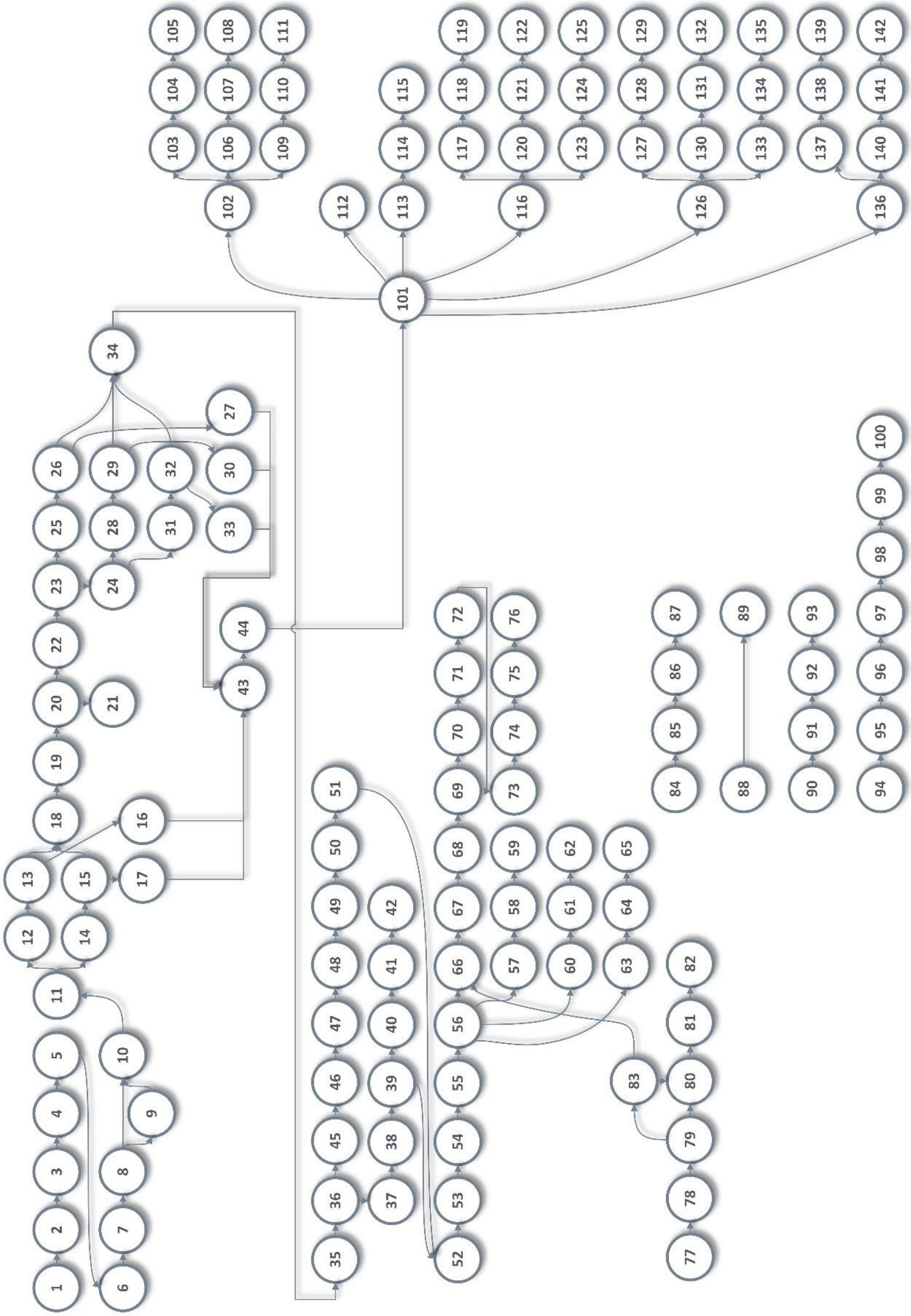
The most important advantage of the waterjet is its ability to cut materials without heat. Thus it does not cause any change of formation in the heat affected zones in metals (Berglund, 2006). To sum up, the advantages of Water Jet Cutting are;

+ As it does not generate heat, it is possible to use in explosive or flammable environments
+ It is accurate and provides perfect, clean cuts.
+ There is no emission from the water jet machine and no emission from the cut material, i.e. it is possible to avoid the heavy metal emission from the paint and metal during cutting.
+ The range of materials it can cut is extensive (glass, metals, composites, stone, concrete and so forth)
+ Simple maintenance

Disadvantages of the waterjet cutting;

– The investment cost of the waterjet is very high
– The separate cost for the abrasive, which cannot be recycled
– The noise of the system (TWI-Global, 2017a)
– Safe handling of the nozzle
– Abrasive waste
– Slow cutting speed

Appendix F: Ship Recycling Process Arena Module Details for Chapter 6



Main Step	Module number	Module name	Module type	Properties
Ship Arrival Step	1	Create ship	Create	MaxArrival 1, Time Between Arrivals 90 Days
	2	Record incoming ships	Record	Count, 1, No, No of ships
	3	Assign properties	Assign	Attribute, Number of ships, number of ships +1 Attribute, Arrival time, TNOW
	4	Ship transfer to yard	Route	Route Time: 0, Destination Type Station, Station Name: Quay
DOCKING	5	Quay	Station	Name: Quay, Station Type, Station
	6	Docking of the ship	Process	Seize Delay Release, Medium, Workers (6), Technical manager (1), Foreman (1), Value Added, TRIA (1, 2, 3) hours
	7	Securing the ship arranging access and equipment	Process	Seize Delay Release, Medium, Workers (6), Technical manager (1), Foreman (1), Value Added, TRIA (0.5, 1, 1.5) hours
PREPARATION FOR RECYCLE - SHORE	8	IHM Necessary	Decide	2 way by chance, 10% True
	9	IHM Survey	Process	Delay, Non-value added, UNIF(1,2) Days
	10	Preinspection and safety check	Process	Delay, Non-value added, EXPO (3) hours
	11	Parallel works	Separate	Duplicate original, 0 cost to duplicate, # of dup: 1
	12	General Cleaning of the ship	Process	Seize Delay Release, Medium, Workers (3), Foreman (1), Value Added, UNIF (3, 5) days
	13	Separate loose items	Separate	Duplicate original, 0 cost to duplicate, # of dup: 11
	14	Discharge fuel and sludge	Process	Seize Delay Release, Medium, Workers (3), Value Added, Normal (2, 0.5) days
	15	Separate liquid waste	Separate	Duplicate original, 0 cost to duplicate, # of dup: 1
	16	Assign loose items	Assign	Entity type: Loose items on ship, Attribute Material index 1
	17	Assign liquid waste	Assign	Attribute Material index 2
	18	Batch parallel works	Batch	Type permanent, Batch size 2, Save criterion Last, Rule Any entity
	19	Removal of hazardous materials	Process	Seize Delay Release, Medium, Workers (3), Value Added, Normal (1, 0.5) days
	20	Separate hazmat	Separate	Duplicate original, 0 cost to duplicate, # of dup: 14
	21	Assign hazmat	Assign	Entity type: Hazardous material,Attribute Material index 3
	22	Authority check	Process	Delay, Non-value added, TRIA (0.5, 1, 1.5) hours
PRIMARY CUTTING - QUAYSIDE	23	Parallel works quay	Separate	Duplicate original, 0 cost to duplicate, # of dup: 1
	24	Parallel works quay 2	Separate	Duplicate original, 0 cost to duplicate, # of dup: 1
	25	Remove cables and electronic equipment	Process	Seize Delay Release, Medium, Workers (3), Value Added, Normal (1, 0.5) days
	26	Separate cables and electronic equipment	Separate	Duplicate original, 0 cost to duplicate, # of dup: 18
	27	Assign cables and electrical	Assign	Attribute Workshop process, 1, Attribute material index 5, Entity type, Cables and electrical
	28	Remove machinery on board	Process	Subprocess
	29	Separate Machinery	Separate	Duplicate original, 0 cost to duplicate, # of dup: 30
	30	Assign machinery	Assign	Attribute material index 6, Entity type, Machinery
	31	Remove insulation flooring tiling	Process	Seize Delay Release, Medium, Workers (3), Value Added, UNIF (0.5, 1.5) days
	32	Separate insulation flooring tiling	Separate	Duplicate original, 0 cost to duplicate, # of dup: 18
	33	Assign insulation flooring tiling	Assign	Attribute material index 4, Entity type, Insulation flooring tiling

	34	Batch parallel works quay	Batch	Type permanent, Batch size 3, Save criterion Last, Rule Any entity
	35	Safety check	Process	Delay, Non-value added, TRIA (0.5, 1, 1.5) hours
	36	Logical separation for primary cutting	Separate	Duplicate original, 0 cost to duplicate, # of dup: 68
	37	Assign steel	Assign	Attribute Material index 7, Entity type, Metal
	38	Primary cutting of blocks on quay	Process	Seize Delay Release, Medium, Workers (1), Value Added, NORM (30, 10) minutes
	39	Decide primary quay	Decide	2 way by chance, 93% True
	40	Transfer to shore	Process	Seize Delay Release, Medium, Workers (1), Crane (1), Operator (1), Transfer, Expression ((95.5 + 40 * BETA(0.396, 0.4)) + 28.5 + 62 * BETA(0.695, 0.657))
	41	Request transport to hazmat storage	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
	42	Transport to hazmat storage	Transfer	Unit number 1, Entity Destination Type: Station, Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
	43	Transfer to shore 2	Process	Seize Delay Release, Medium, Workers (1), Crane (1), Operator (1), Transfer, Expression ((95.5 + 40 * BETA(0.396, 0.4)) + 28.5 + 62 * BETA(0.695, 0.657))
	44	Quay shore	Station	Quay Shore, Station
TRANSFER TO RAMP	45	Logical delay	Delay	Allocation: Other, Delay Time: 1 Seconds
	46	Hold to finish all work	Hold	Type: Scan for Condition, Condition: "Primary cutting of blocks on quay.WIP == 0 && NQ(Primary cutting of blocks on quay.Queue) == 0"
	47	Pull the barge up the ramp with chainpuller and tugboats	Process	Delay, Transfer, TRIA (0.5, 1, 1.5) hours
	48	Ramp	Station	Ramp, Station
	49	Secure	Process	Seize Delay Release, High (1), Workers (3), Foreman (1), Non-Value Added, NORM (10, 2) minutes
CUTTING AND DISMANTLING ON THE RAMP	50	Separate logic cutting on ramp	Separate	Duplicate original, 0 cost to duplicate, # of dup: 600
	51	Cutting blocks on ramp	Process	Seize Delay Release, Workers (1), Medium, UNIF (20,40) minutes
	52	Transfer to Secondary dismantling zone	Process	Seize Delay Release, Medium, Workers (1), Crane (1), Operator (1), Transfer, Expression (95.5 + 40 * BETA(0.396, 0.4)) + (28.5 + 62 * BETA(0.695, 0.657)) + EXPO(240)
	53	Secondary dismantling zone	Station	Secondary zone, Station
SECONDARY CUTTING OF BLOCKS	54	Secondary cutting of blocks	Process	Seize Delay Release, Medium, Workers (1), Value Added, TRIA(40, 60, 80) minutes
	55	Logical separation for plate number	Separate	Duplicate original, 0 cost to duplicate, # of dup: TRIA (15, 20, 25)
	56	Decide secondary zone	Decide	N-way by chance (69,24,5,else)
	57	Request transport to SGZ from SZ	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
	58	Load delay	Delay	Other: 2 Minutes
	59	SZ to SGZ	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Segregation Zone, Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
	60	Request transport to WS from SZ	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
	61	Load delay 2	Delay	Other: 2 Minutes
	62	SZ to WS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Workshop, Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination

	63	Request transport to HZM from SZ	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
	64	Load delay 3	Delay	Other: 2 Minutes
	65	SZ to HZM	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Hazardous material storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
TRANSPORT TO LOADING ZONE	66	Request transport to loading zone	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
	67	Load delay 17	Delay	Other: 2 Minutes
	68	Transport to loading zone	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Loading zone Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
	69	Loading	Station	Station, Loading zone
	70	Unload delay 4	Delay	Other: 2 Minutes
	71	Free 5	Free	Free: Transporter, Unit number 1
TRANSPORT OUT OF YARD	72	Batch for loading to trucks	Adjustable Batch	Temporary batch, Optimum batch size: 20, Partial batch method maximum wait time, maximum wait time: 1 days
	73	Separate the batch	Separate	Split existing batch
	74	Loading to trucks	Process	Seize Delay Release, Medium, Operator (1), Polygrab (1), Value Added, NORM(17.5, 4.56)
	75	Out	Station	Station, Out
	76	Leave the yard	Dispose	-
SEGREGATION ZONE	77	Segregation	Station	Station, Segregation
	78	Free 3	Free	Free: Transporter, Unit number 1
	79	Segregation decide	Decide	N-way by condition, Attribute, Material index ==1 , Attribute, Material index ==4, Else
	80	Request transport to NHS from SGZ	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
	81	Load delay 4	Delay	Other: 2 Minutes
	82	Transport metal to NHS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
	83	Segregation decide metal	Decide	2 way by chance, 90% True
STORAGE IN THE YARD	84	NONHAZMAT	Station	Station, Non Hazmat Storage
	85	Unload delay 1	Delay	Other: 2 Minutes
	86	Free 2	Free	Free: Transporter, Unit number 1
	87	Nonhazmat leave	Dispose	-
	88	Liquid waste	Station	Station, Liquid waste storage
	89	Liquid waste leave	Dispose	-
	90	HAZMAT Store	Station	Station, Hazardous material storage
	91	Unload delay 2	Delay	Other: 2 Minutes
	92	Free 4	Free	Free: Transporter, Unit number 1
	93	Hazmat leave	Dispose	-
	94	Workshop	Station	Station, Workshops
	95	Unload delay 3	Delay	Other: 2 Minutes
	96	Free 1	Free	Free: Transporter, Unit number 1
	97	Process in workshop	Process	Seize Delay Release, Low, Workers (1), Value Added, TRIA (1, 2, 3)
	98	Request transport from WS	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
	99	Load delay 18	Delay	Other: 2 Minutes
	100	Transport to NHS from WS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
TRANSPORT IN YARD	101	Decide where	Decide	N-way by condition, Attribute, Material index==1, Material index==2, Material index==3, Material index==4, Material index==5, Else
	102	Loose items	Decide	N-way by chance (6, 56), Else

103	Request transport to SGZ	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
104	Load delay 5	Delay	Other: 2 Minutes
105	Transport to SGZ	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
106	Request transport to NHS	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
107	Load delay 6	Delay	Other: 2 Minutes
108	Transport to NHS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
109	Request transport to HAZM	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
110	Load delay 7	Delay	Other: 2 Minutes
111	Transport to HZM	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
112	Route of liquid waste	Route	Route Time: 0, Destination Type Station, Station Name: Liquid waste storage
113	Request transport to HZM 2	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
114	Load delay 8	Delay	Other: 2 Minutes
115	Transport to HZM 2	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
116	Decide insulation flooring tiling	Decide	N-way by chance, (24, 15), Else
117	Request transport to HZM for ins	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
118	Load delay 12	Delay	Other: 2 Minutes
119	Transport ins to HZM	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
120	Request transport to SGZ for ins	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
121	Load delay 13	Delay	Other: 2 Minutes
122	Transportation to SGZ	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
123	Request transport to NHS for ins	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
124	Load delay 14	Delay	Other: 2 Minutes
125	Transport ins to NHS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
126	Decide cables and electrical equipment	Decide	N-way by chance, (24, 22), Else
127	Request transport to HZM for electronic waste	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
128	Load delay 9	Delay	Other: 2 Minutes
129	Transport electronic waste to HZM	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination

130	Request transport to WS for electronic equipment	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
131	Load delay 10	Delay	Other: 2 Minutes
132	Transport electronic equipment to WS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
133	Request transport to NHS for electronic equipment	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
134	Load delay 11	Delay	Other: 2 Minutes
135	Transport electronic equipment to NHS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
136	Decide machinery	Decide	Decide machinery, True: 7%
137	Request transport to WS for machinery	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
138	Load delay 15	Delay	Other: 2 Minutes
139	Transport machinery to worksop	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination
140	Request transport to NHS for machienry	Request	Selection Rule: Smallest Distance, Priority: High, Entity Location: Entity Station, Velocity: 1.38 per second
141	Load delay 16	Delay	Other: 2 Minutes
142	Transport machienry to NHS	Transfer	Unit number 1, Entity Destination Type: Station, Station name; Non hazmat storage Velocity: 1.38 per second, Guided Tran Dest Type: Entity Destination