Improving the Competitiveness of Green Ship Recycling

Kanu Priya Jain

Propositions

accompanying the thesis

Improving the Competitiveness of Green Ship Recycling

from

Kanu Priya Jain
Sep 8, 2017
Delft University of Technology

1. The availability of a downstream market for second-hand goods is essential for a ship recycling yard to become competitive. (This thesis)

2. The lack of co-ordination between the stakeholders of the ship recycling industry is detrimental to cost-effective green ship recycling. (This thesis)

3. A ship cannot be called 'futuristic' until it is designed in such a way that it can also be recycled easily.

4. The more efficient and reliable the transportation system is, the more traumatic a deficiency will be for commuters.

5. The global climate will be better-off without UN climate change conferences.

6. Cooking is like a Chemistry experiment, quantity of each ingredient has a major influence on the end result.

7. Social media is a catalyst for exhibitionism, narcissism and depressions.

8. Assumptions are the most effective tool for a successful research.

9. The greatest hurdle to finish a thesis on time is procrastination.

10. Other than the traditional news media, daily commuting is the best way to be aware of local events.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotor prof. ir. J.J. Hopman and copromotor dr. ir. J.F.J. Pruyn.

IMPROVING THE COMPETITIVENESS OF GREEN SHIP RECYCLING

Kanu Priya Jain

TU Delft
Delft
University of
Technology

TIANJIN UNIVERSITY (PEIYANG UNIVERSITY)
北洋
1895
天津大学

ISRA
International Ship Recycling Association

GIESKES·STRIJBIS FONDS

Lloyd's
Register

DAMEN

中华人民共和国
环境保护部
Ministry of Environmental Protection
The People's Republic of China

SEA
2
CRADLE

Stichting
De Noordzee

IMPROVING THE COMPETITIVENESS OF GREEN SHIP RECYCLING

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. ir. K.C.A.M. Luyben,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op
vrijdag 8 september 2017 om 10:00 uur

door

Kanu Priya JAIN

Bachelor of Science in Marine Engineering, Birla Institute of Technology and Science, Pilani, India
Master of Science in Marine Transport Management, Newcastle University, U.K.
geboren te Ghaziabad, India

This dissertation has been approved by the
promotor: Prof. ir. J.J. Hopman
copromotor: Dr. ir. J.F.J. Pruyn

Composition of the doctoral committee:

Rector Magnificus	*Chairperson*
Prof. ir. J.J. Hopman	*Delft University of Technology*
Dr. ir. J.F.J. Pruyn	*Delft University of Technology*
Independent members:	
Prof. dr. A. Magerholm-Fet	*Norwegian University of Science and Technology*
Prof. dr. O. Turan	*University of Strathclyde, Glasgow*
Prof. dr. A.R. Balkenende	*Delft University of Technology*
Prof. dr. ir. P.H.A.J.M. van Gelder	*Delft University of Technology*
Dr. Y. Yang	*Delft University of Technology*

The research described in this thesis was carried out at Delft University of Technology, The Netherlands for a project collaborated with Tianjin University, China and International Ship Recycling Association (ISRA); funded by Gieskes Strijbis Fonds, Lloyd's Register, Damen Shipyards Group and Ministry of Environmental Protection, Government of China; and supported in-kind by Stichting De Noordzee, Sea2Cradle B.V. and other ISRA members.

Keywords: ship recycling; ship breaking; design-for-recycling; waste management; economic analysis; material flow analysis

ISBN 978-94-6299-657-1
Printed and bound by: Ridderprint BV, The Netherlands
Cover design and layout: K.P. Jain

Contact: kanu.p.jain@gmail.com

An electronic version of this thesis is available at *http://repository.tudelft.nl*

To my better half

Summary

The end of life of a ship is determined by its owner on the basis of various commercial and technical factors. Once decided to scrap a ship, almost all end-of-life (EOL) ships are sold to recycling yards for dismantling; except for a few which are converted into museums, hotels, storage, and artificial reefs. As the decision is a commercial one, the selection of a yard is predominantly based on the offer price, which depends on the location of the yard and the recycling process employed.

Amongst major recycling centres, generally the yards located in the Indian subcontinent offer more than the Chinese yards, and Turkish yards offer the lowest of the three. Also, within these countries, the yards compliant with the international regulations and safety standards (green), and non-compliant yards (substandard/non-green) co-exist. The contrasting difference in offer price between the two makes the non-green yards more lucrative. Since the regional difference in price is due to perpetual local factors, this research focuses mainly on improving the competitiveness of green yards, irrespective of the region. The aim is to reduce the economic incentive to use substandard yards.

The concept of ‘cleaner production’ is applied to solve the research problem, which identified three main measures. First, the material flow analysis (MFA) to improve the planning and awareness on the yard. Second is the use of a waste-to-energy (WtE) technology to improve the valorisation of waste. And third, the use of the design-for-recycling (DfR) concept to improve the recyclability of new ships. The quantification of material streams of EOL ships is also suggested to support these measures.

A ‘material quantification model’ based on the ship’s lightweight distribution is developed to enable yards to quantify the material streams of EOL ships. Standardizing the format of lightweight distribution will ensure the speedy determination of material streams of EOL ships. The classification societies could play a leading role in implementing this simple yet effective solution.

An MFA model driven by the output of the first model (quantified material streams of the ship) is suggested to conduct analyses on recycling yards. An MFA can effectively be used by yards to conduct several planning related tasks; most importantly, to determine the amounts of materials generated for disposal (waste) and recycling. Therefore, yards are recommended to plan the ship recycling process using the MFA results.

For the WtE technology, the use of a plasma gasification plant on a large recycling yard (capacity of at least 1 million LDT per year) is estimated to increase the offer price in the range of $0.24 to $7.31 per LDT, depending on the recycling rate and plant size. The application of a plasma gasification plant is limited to the large size yards located predominantly in China as against the small to medium size yards in the subcontinent.

While comparing the industry in the Indian subcontinent with China/Turkey, upgrading the non-green yards is also a possibility to bridge the price gap. The upgrade of an existing pier-breaking facility up to the Hong Kong convention standards is estimated to reduce the offer price in the range of $4 to $9 per LDT. For other facility types, the reduction is likely to be in the range of $10 to $35 per LDT, depending on the facility type, recycling capacity and the upgrade cost.

For the DfR concept, the ship design features useful for reverse production, such as modular accommodation and lifting supports, amongst others, are suggested. A new format of the ship's lightweight distribution is also proposed as a documental change to the ship design. Although these features will not reduce the offer price gap between the green and non-green yards as both yard types bear the same advantages of new design features, the recycling operations will definitely be streamlined and offer prices in general will be improved.

When all four improvements are combined and applied on the three major regions, it is clear that a gap of about 20 $/LDT and 30 $/LDT will remain between green and non-green yards in Turkey, and the Indian subcontinent respectively. However, in China, the gap can be reduced well within the range of 5 $/LDT. What also becomes clear is the availability of a much better developed downstream market in the Indian subcontinent will still ensure that prices offered here are about 25 $/LDT and 100 $/LDT higher than in China and Turkey respectively. The fact that components can be sold instead of just scrap materials is an important factor in this.

Samenvatting

Het einde van het leven van een schip wordt bepaald door de eigenaar op basis van verschillende commerciële en technische factoren. Nadat eenmaal de beslissing is genomen het schip te slopen, worden bijna al deze schepen verkocht aan recycling yards voor ontmanteling; Met uitzondering van enkele die worden omgezet in musea, hotels, opslag en kunstmatige riffen. Aangezien de beslissing om te slopen commercieel is, is de keuze van een werf hoofdzakelijk gebaseerd prijs die zij voor het schip bieden. Deze is weer afhankelijk van de locatie van de werf en het recycle-proces dat wordt gebruikt.

Van de belangrijkste recyclingcentra, bieden de werven in het Indiase subcontinent meestal meer dan de Chinese en Turkse werven. Deze laatste bieden de laagste prijs van de drie. In ieder van deze landen bestaan er werven die voldoen aan de internationale regelgeving en veiligheidsnormen (groen), en werven die hier niet aan voldoen (ondermaatse/niet-groen). Het verschil in aanbodprijs tussen de twee maakt de niet-groene werven lucratiever. Aangezien het regionale prijsverschil te wijten is aan vaste lokale factoren, concentreert dit onderzoek vooral op het verbeteren van het concurrentievermogen van groene werven, ongeacht de regio. Het doel is om de economische prikkel te verminderen die reders laat kiezen voor ondermaatse werven te gebruiken.

Drie hoofdmaatregelen van het concept 'schonere productie' worden toegepast om het onderzoeksprobleem op te lossen. Ten eerste, de materiaalanalyse (MFA) om de planning en het bewustzijn op de werf te verbeteren. Ten tweede, het gebruik van een afval-naar-energie-technologie (WtE) om de valorisatie van afval te verbeteren. En ten derde, het gebruik van het ontwerp-voor-recycling (DfR) concept om de recycleerbaarheid van nieuwe schepen te verbeteren. Daarnaast wordt de kwantificering van materiaalstromen van sloopschepen wordt ook voorgesteld om deze maatregelen te ondersteunen.

Een 'materiaal kwantificatie model', gebaseerd op de lichtgewichtverdeling van het schip, is ontwikkeld om werven in de gelegenheid te stellen de materiaalstromen van sloopschepen te kwantificeren. Het standaardiseren van het formaat van deze lichtgewicht verdeling zorgt voor een snelle bepaling van materiaalstromen van sloopschepen. De classificatiebureaus zouden een belangrijke rol kunnen spelen bij de uitvoering van deze eenvoudige maar effectieve oplossing.

Een MFA-model dat wordt aangedreven door de output van het eerste model (gekwantificeerde materiaalstromen van het schip) wordt voorgesteld om analyses op recycling yards uit te voeren. Een MFA kan effectief worden gebruikt door yards om verschillende planning gerelateerde taken uit te voeren; Belangrijker nog, om de hoeveelheden materialen die zijn geproduceerd voor vernietiging (afval) en recycling te bepalen. Daarom worden werven aanbevolen om het scheepsrecyclingproces te plannen met behulp van de MFA-resultaten.

Voor de WtE-technologie wordt het gebruik van een plasma vergassingsinstallatie op een grote recyclingwerf (capaciteit van minstens 1 miljoen LDT per jaar) onderzocht. Naar verwachting zal de aanbodprijs in tussen de $0,24 en $7,31 per LDT verhoogd kunnen worden, afhankelijk van het recyclingpercentage en werfomvang. De toepassing van een plasma vergassingsinstallatie is beperkt tot de grote sloopwerven die zich hoofdzakelijk in China bevinden en minder geschikt voor de kleine tot middelgrote werven in het subcontinent.

Als de industrie in het Indiase subcontinent met China / Turkije wordt vergeleken, is de upgrade van de niet-groene werven ook een mogelijkheid om het prijsverschil te overbruggen. De opwaardering van een bestaande sloopfaciliteit met een pier naar de Hong Kong conventie standaarden wordt geschat op een verlaging van de aanbodsprijs van tussen de $4 en $9 per LDT. Voor andere faciliteit typen is de verlaging waarschijnlijk in tussen de $10 en $35 per LDT, afhankelijk van het type apparaat, recyclingcapaciteit en de upgradekosten.

Voor het DfR-concept worden de ontwerpaspecten van het schip, die nuttig zijn voor een omgekeerde productie, zoals modulaire huisvesting en hijsondersteuning, voorgesteld. Een nieuw aanpak van de lichtgewichtverdeling van het schip wordt ook voorgesteld als een aanpassing van de documenten geleverd vanuit het scheepsontwerp. Hoewel deze eigenschappen het prijsverschil tussen de groene en niet-groene werven niet zullen verminderen, omdat beide werftypes dezelfde voordelen hebben van nieuwe ontwerpfuncties, zullen de recyclingactiviteiten zeker gestroomlijnd kunnen worden en zullen de aanbodprijzen in het algemeen worden verbeterd.

Wanneer alle vier verbeteringen gecombineerd en toegepast worden in de drie grote regio's, is het duidelijk dat een kloof van ongeveer 20 $/LDT tot 30 $/LDT tussen groene en niet-groene werven in Turkije en het Indiase subcontinent zal blijven. In China kan de kloof echter goed worden verlaagd binnen het bereik van 5 $/LDT. Wat ook duidelijk wordt, is dat de beschikbaarheid van een veel beter ontwikkelde afzetmarkt in het Indiase subcontinent, garandeert dat de hier aangeboden prijzen ongeveer 25 $/LDT tot 100 $/LDT hoger zijn dan in respectievelijk China en Turkije. Het feit dat componenten in plaats van alleen schrootmaterialen kunnen worden verkocht, is hierbij een doorslaggevende factor.

Acknowledgements

As rightly said by Dr. Raghuram Rajan, an Indian economist and former Chief Economist at International Monetary Fund, *“A book is almost always a collective effort, even if it has only a single author”*, this work would not have come into existence without the support and guidance of several people throughout the course of my Ph.D. program. I would like to acknowledge and appreciate the efforts of those who supported and helped me achieve the goal of obtaining a doctoral degree.

To begin with, I would like to thank my supervisory team. Jeroen, over the last four years you have been an excellent mentor and guide to me. The doctoral program would have been very arduous without your guidance and motivation, especially through the initial period of the research when I was struggling to arrange the requisite data. Every time I went back to my office after having a meeting with you, I was full of new ideas, motivation and enthusiasm to take the research in the right direction. Also, special thanks for helping me formulate the Dutch summary of the thesis. And Hans, I cannot thank you enough for supporting me throughout the doctoral journey. Whether approving my participation in a conference, a course or a visit to a recycling yard, you have always been supportive. Your ‘open-door’ policy has always amazed me. You were available whenever I needed to have a discussion with you. Although you had a very busy schedule, you were always keen to provide critical feedbacks to my work. I would like to appreciate you for showing faith in me after the first go/no-go meeting.

I thank all my colleagues for sharing such a vast amount of knowledge and experiences, and for providing a fruitful social and working environment. Specifically, first I would like to thank my office mates, most importantly Guangming, for becoming a true companion at TU Delft and for sharing the highs and lows of my doctoral journey, Breno, for having great conversations about diverse topics, and Qinqin, for providing inputs to improve the proof print. Second, I must thank all my previous office mates, Marcella, Masoud, Xiaojie and Peijuan for cordially sharing the same office space. Third, I am grateful to Guangming, Elena, Harsh, Qinqin and Daijie for sharing innumerous lunches and having amazing conversations. Fourth, I would like to extend my gratitude to the SDPO guys – Milinko, for extending a personal touch to our collegiality; Jenny, for providing a warm welcome to the department and introducing me to the Dutch directness on my first day to the office; Peter and Arthur, for all your smiles and greetings while walking through the aisles; Etienne, for all your help as a fellow Ph.D. student; and Chris, for being the wittiest person of our group, and of course for proofreading my articles as well. And finally, a big appreciation for our ex and current support staff – Ria, Jozephina, Anouk, Patty, Monique and Dineke.

During the course of my research, I also had the privilege to supervise a few Bachelor's and Master's students. I would like to appreciate the contribution of Robin, Daan, Rep and Maurice towards the Bachelor-end project on design-for-recycling. The effort put in by Emanuele on design-for-recycling and by Sander to collect data and information from Chinese recycling yards is much appreciated.

It is an appropriate time to acknowledge the support of the project partners. Tom Peter, I would like to thank you and your colleagues at Sea2cradle for providing invaluable insights into the ship recycling industry and for all the efforts taken to arrange the visits to the ship recycling yards through your professional network. Jim, I am indebted to you and your colleagues at Lloyds Register for providing necessary information for the research. Some critical analyses of this research would not have been possible without your support. Thank you for offering an unconditional support. Bernard, I greatly appreciate your chairmanship at the steering committee meetings of the project. It immensely helped the project to be successful. And finally, the support of all the professors and students of Tianjin University, China who were involved in the project is much appreciated. Their involvement added another dimension to the overall project.

To conclude, I would like to thank my family. First, my parents; Mummy and Papa, I can never thank you enough in my lifetime. Your love, support and motivation was critical for me to successfully sail through the uncharted territories of the doctoral program. Second, my brother; Manu, I thank you for being critical as well as supportive. Your frequent banters kept me going. Third, my in-laws, their support and encouragement helped me a lot. And last but not the least, the apple of my eye, my wife; Stuti, I thank you for giving me a reason to embark upon such a special journey in life. You were not just the driving force behind the inception of my Ph.D. but you also stood by my side throughout the course of it. You were my support system. No words are enough to thank you.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

"Setting goals is the first step in turning the invisible into the visible."

- Tony Robbins (1960 – present), Author

Historically, ships have been important to humans, transporting commodities, commercial goods and people through oceans and seas and protecting these interests with navies. The ships have played a vital role in shaping today's globalized world, where about 80% of the global trade by volume and 70% by value is carried by sea (Asariotis et al., 2012). However, like every product, ships too have a limited lifetime.

The end of life of a ship is sometimes sudden, when it is lost at sea; but most of the times, it is primarily determined by a ship owner on the basis of commercial and technical factors (Stopford, 2009). An important question for a ship owner is how to discard a ship that has reached the end of its useful life. A few ships end up as museums, hotels, storage facilities and tourist attractions, some are still sunk in order to make artificial reefs (Ahuja et al., 2011), yet most of the end-of-life (EOL) ships end up in ship recycling yards for their 'last rites'.

The International Maritime Organization (IMO) recognizes 'ship recycling' as the best option for the ships that have reached the end of their operating lives because it is considered to contribute to the economic and sustainable development of the society (IMO, 2009). There are several reasons for this. First, the ship recycling industry is instrumental in providing hundreds of thousands of jobs to skilled, semi-skilled and unskilled workers in developing countries such as China, India, Pakistan and Bangladesh (Dev, 2010, Sarraf, 2010).

Second, ship recycling recovers millions of tons of ferrous and non-ferrous metal scrap for recycling and an enormous amount of machinery, equipment and other fittings for reuse from end-of-life (EOL) ships annually (Crang et al., 2013, Gregson et al., 2012, Hiremath et al., 2015, Mizanur Rahman and Mayer, 2015). According to the French NGO Robindesbois.org (2006-16), the global ship recycling industry recycled at least 7 million tons of scrap metal every year since 2011. This figure touched the 11 million mark in 2012 when a record number of ships (1328) were scrapped.

Lastly, it provides a substantial amount of re-rollable and melting scrap steel for the iron and steel industries in South Asian countries (Sarraf, 2010). For example, Mikelis (2013b) estimated that in 2011, the ship recycling industry contributed about 71% of the ferrous scrap required by the steel making industry of Bangladesh. In this way, resources and energy are conserved, and greenhouse gas emissions, air pollution and water pollution are reduced (Söderholm and Ejdemo, 2008), due to a reduced need for mining metals and other natural resources.

The ship recycling industry is also an essential part of maritime business and economics. It deals in ships for scrapping and is a source of cash inflow for ship owners during the times of recession. In a freight market with an oversupply of ships, the scrapping of ships controls the growth rate of the merchant fleet and helps in equalizing the demand and supply of ships for maritime transportation by removing obsolete ships from the market. The removal and reduced supply of ships help in a recovery of freight rates as a result of balanced supply and demand of ships in the freight market (Stopford, 2009).

On the contrary, the ship recycling industry poses threats to the environment and health and safety of the workers dismantling EOL ships, as indicated by a plethora of studies, some of which are cited in a recent EU publication – Science for Environment Policy (SEP, 2016). The primitive practices employed by several ship recycling yards around the world undermine the contribution of the industry towards sustainability. In order to prevent such hazards, IMO adopted the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (IMO, 2009) in May 2009. However, it is not yet enforced.[*]

The convention is commonly called as Hong Kong convention (HKC). It defines ship recycling as "the activity of complete or partial dismantling of a ship at a ship recycling facility in order to recover components and materials for reprocessing and re-use, whilst taking care of hazardous and other materials" (IMO, 2009). The definition includes associated operations such as on-site storage and treatment of components and materials as part of ship recycling, but further processing or disposal of the recovered components and materials in separate facilities is not included.

Ship recycling is also referred to by several other terms such as ship breaking, ship dismantling, ship scrapping, ship demolition and ship disposal, to name a few. Although each term has a slightly different meaning and the context in which it is used, they all refer to the same activity, i.e., dismantling of end-of-life ships. For example, 'ship breaking' is generally used in the context of South Asian countries, 'ship dismantling' is used by the Basel convention (discussed in Chapter 2), 'ship scrapping' is used by ship owners, 'ship demolition' is used by ship brokers and

---

[*] The convention is discussed in detail in Chapter 2.

‘ship disposal’ is often used in shipping statistics (Mikelis, 2012). Due to lack of any formal definition of most of these terms, they are normally used interchangeably. The same practice is also followed in this dissertation. However, ‘ship recycling’ is used more often because it is defined formally by the Hong Kong convention.

According to the World Bank (Sarraf, 2010), the process of taking a ship apart with procedures to safeguard the environment and workers' health and safety in place is known as ‘green recycling’. The ship recycling yards compliant with either the international standards for health, safety and environmental (HSE) management or the international ship recycling regulations (For example, HKC and EU ship recycling regulation) are considered innocuous to environment, health and safety of the workers, and are referred to as ‘green’ recycling yards in this dissertation. Other yards which do not follow HSE management standards and relevant regulations are referred to as ‘substandard’ or ‘non-green’ recycling yards.

The green ship recycling yards are not very popular among a large number of ship owners due to their inability to offer a good price compared to substandard yards. The price gap between the two is mainly due to the extra cost of maintaining high HSE standards and investment in recycling facilities and workforce welfare required for green ship recycling (Dev, 2010). The cost of the total process must be lower than the income for a recycling yard to be profitable. Therefore, the green yards cannot match the price offered by the substandard yards employing primitive recycling techniques. They can become more competitive only when the price gap between the two is reduced or even closed.

Based on the discussion so far, the research objectives and the main research question to be answered are described in the next section of this chapter. The key research questions that must be answered to seek an answer to the main research question are also formulated. The structure of the dissertation and the subject of discussion of each of the subsequent chapter are discussed in Section 1.2 of this chapter.

1.1 Research objectives

The main research question of this dissertation is *how green ship recycling yards can improve their competitiveness against substandard ship recycling yards?*

The term *competitiveness* used in the research question pertains to the ability of green ship recycling yards to offer a similar or even a better price for buying an end-of-life ship. This can only be done by increased revenue and/or reduced costs of green ship recycling yards. The improved planning of the ship recycling process is also required by the procedures laid out by not-yet-enforced international regulations on ship recycling (discussed in Chapter 2).

Therefore, this dissertation aims to explore and apply strategies that can help recycling yards improve planning, reduce recycling costs and increase revenues considering the forthcoming international ship recycling regulations. This is likely to holistically improve the ship recycling industry in general and green ship recycling in particular.

Such objectives can be achieved by strategizing the ship recycling process using the scientific methods, tools and techniques. A strategy to improve revenue could be to find extra sources of income from the recycling process whereas costs of the recycling process could be reduced by improving the operations at the yard. Certain changes in the future ship designs could also be helpful in achieving both reductions in costs and increase the income from recycled materials.

An in-depth study of the process of recycling a ship will help us improve the operations and planning of the recycling process. A close look at the ship recycling process allows us to understand the fact that its major outputs include reusable materials/components, recyclable materials/components and waste. Therefore, creating value from the waste is a way forward to improve the competitiveness of green recycling yards (as yards already earn from reusable and recyclable outputs).

The study of the ship recycling process may also help us understand what ship design features are unfavourable to ship recycling. Based on this feedback, existing ship designs could be improved. Therefore, possible changes to ship designs could also be explored. However, any positive effect of design changes could only be seen 20 to 30 years later when ships with improved design reach the end of their lives.

Before finding an answer to the research question, it is also important to understand in detail what is green ship recycling and how does it differ from the substandard ship recycling. Therefore, the ship recycling industry must be studied thoroughly including the existing and future international regulations applicable to it. The impact of future ship recycling regulations on various stakeholders such as ship recycling yards, ship owners, ship building yards, and others must also be studied.

Such discussion will provide the background to the aims and objectives of the research.

Another important aspect to consider is whether the yards located in one region can become competitive against the yards located in another region and if so, to what extent. To do so, it is imperative to understand the characteristics of and prevailing practices in the yards of major recycling locations.

The research objectives and the main research question lead to the following key research sub-questions:

1. What is the current state of the global ship recycling industry and what is the difference between the green and substandard ship recycling?
2. How to decide what measures can be applied to a ship recycling yard to achieve the stated objectives of the research?
3. What are the quantities and types of material streams available on an end-of-life ship?
4. How can recycling yards plan the disintegration of a vessel into recyclable products and waste?
5. How can recycling yards turn the waste generated during the recycling process into revenue?
6. What design changes can be made to a ship to increase the cost-effectiveness of green ship recycling?

1.2 Structure of the dissertation

The dissertation is structured as shown in Figure 1.

Chapter 2 provides an in-depth overview of the ship recycling industry and associated international regulations. Major recycling locations are discussed with respect to the differences in their characteristics such as volume of ships, scrap prices and recycling process employed. Together with the introduction, it forms the prologue to this research.

Chapter 3 introduces the concept of Cleaner Production (CP). It is used to decide what kinds of strategies are applicable to the ship recycling industry to achieve the objectives discussed in this dissertation. These strategies provide a road map for this research. Each of these strategies is defined and applied to the ship recycling industry in the subsequent chapters. The effect of implementing these strategies in achieving the research objectives is also discussed.

Chapter 4 develops and discusses a material quantification model because the improvement strategies discussed in Chapters 5 and 6 require the quantification of materials of EOL ships.

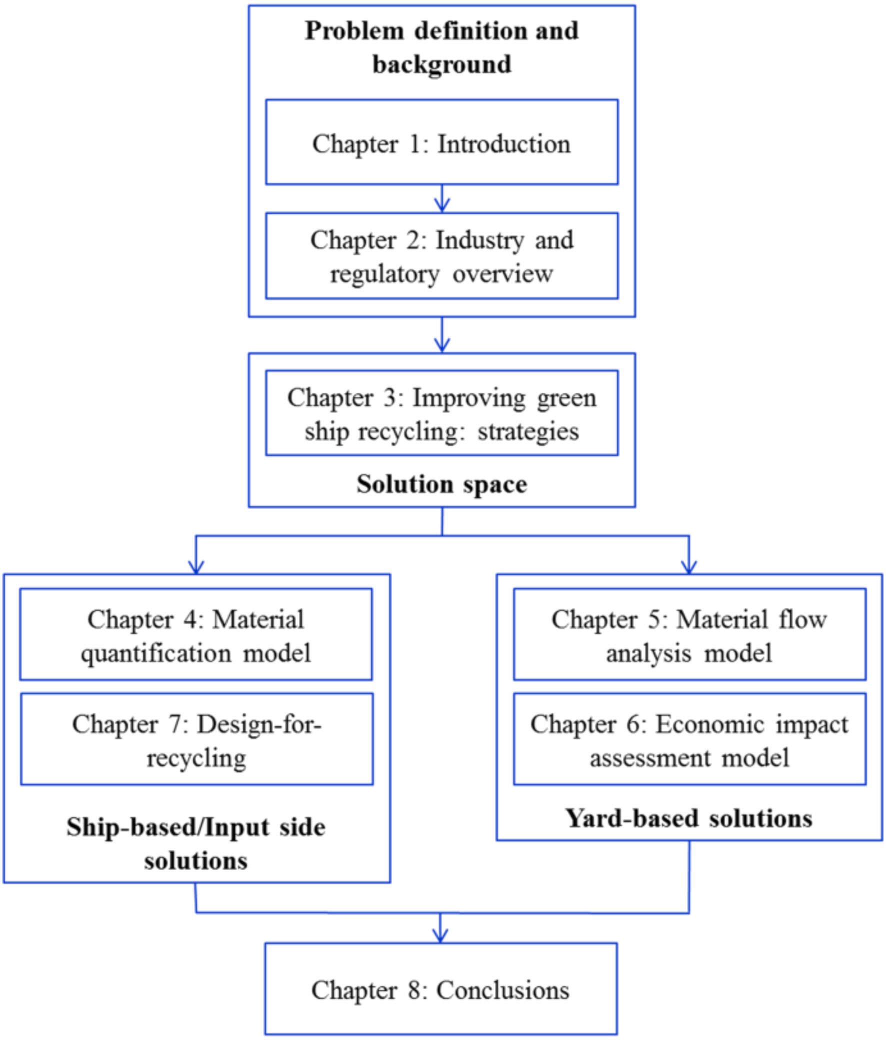


Figure 1.1: Structure of the dissertation

Chapter 5 describes a material flow analysis model which can be used by ship recycling yards to analyse the flow of materials originating from the EOL ships to better plan the ship recycling process.

Chapter 6 describes an economic assessment model that can be used by ship recycling yards to understand the effect of using new technologies (for improving the ship recycling process and its revenue) to the price offered to buy an EOL ship.

Chapter 7 discusses the concept of ‘design-for-recycling’ within the context of the ship recycling industry. The impacts of ship design on ship recycling are discussed. The concept is implemented on a bulk carrier as a case study.

Chapter 8 summarizes the results obtained in this research and recommends the future course of research. It also discusses the answers to the research main question and sub-questions obtained during the course of this research. The role of the suggested measures in bridging the gap between the offer prices of green and non-green yards for both inter and intra-region cases is discussed. To conclude, the original contribution of this research to the existing knowledge is reflected.

CHAPTER 2

INDUSTRY AND REGULATORY OVERVIEW[†]

"Truth in science is always determined from observational facts."

\- David Douglass (1932 – present), Physicist

[†] The article based on this chapter accepted for publication can be found as

Jain, K.P. & Pruyn J. 2017. An overview of the global ship recycling industry. *Reference Module in Materials Science and Materials Engineering*, Elsevier Inc., ISBN: 978-0-12-803581-8

The previous chapter discussed the importance of understanding the current state of the global ship recycling industry to answer the research questions dealt with in this dissertation. Therefore, this chapter presents an overview of the ship recycling industry and the relevant international regulations governing the recycling of end-of-life (EOL) ships. It forms a background to the research carried out in this dissertation.

The industry overview is presented by providing insight into three Ws – when, why and where ship recycling is carried out. This chapter also provides an insight into the methods used for recycling, transaction terms and conditions, and the historic volumes of EOL ships globally.

The regulatory overview is presented by discussing the provisions of the Basel Convention, the Hong Kong Convention and EU ship recycling regulation. The final section of the chapter explains what green ship recycling is and what criteria, based on the international regulations, can be used to identify a green ship recycling yard.

2.1 Industry overview

2.1.1 When and why are ships recycled?

The answer to why ship recycling is carried out is rightly put by Stopford (2009) as: “scrapping will occur only when the industry’s reserves of cash and optimism have been run down”. Ship recycling is carried out to remove inefficient ships out of the market, which in turn generates cash flow for ship owners and tackles oversupply of ships in the freight market. Ship recycling, besides being a business decision for the ship owners, is also necessary for the continued renewal of the shipping fleet. Naturally, the oldest ships are removed first due to their high maintenance costs.

A large-scale scrapping of ships is carried out only when the entire shipping industry does not anticipate any prospects of employing ships profitably in the foreseeable future or when the companies need cash urgently (Stopford, 2009). According to Buxton (1991), scrapping is the most attractive option for the ship owners when the prospects of anticipated profitability of a ship are poor and the second-hand prices are correspondingly low. If the market is expected to improve before the technical life of the vessels ends, they are usually laid-up in anchorage outside a port instead of recycled.

The decision to recycle a ship is based on the following factors (Buxton, 1991, Stopford, 2009):

- obsolescence,
- current earnings,
- future market expectations, and
- scrap prices.

These factors regulate the demand and supply dynamics of both – the ship recycling market and the freight market because most ships that are taken out of the freight market are supplied to the ship recycling market. In one way or the other, these factors affect the finances of a shipping company as explained in the subsequent sections.

2.1.1.1 Obsolescence of ships

Obsolescence of a ship depends on several factors including physical, technical, and regulatory. Therefore, a wide range of ages of the ships sent for recycling can be observed in the datasets recorded for ship recycling. For example, Buxton (1991) observed a minimum age of 8 years and a maximum age of 80 years for the 248 ships scrapped in 1984. The average age of the ships sent for scrapping is generally considered about 25-30 years (Kagkarakis et al., 2016). However, Knapp et al. (2008) determined the average age of ships at which they are recycled as 22 years, based on a dataset of ships over 100 gross tonnage (GT) recycled over a period of 7 years from 2000 to 2007.

a) Physical obsolescence

The physical deterioration of ships due to ageing is a natural process which takes place gradually. As the ship grows old, wear and tear of its hull and machinery increases. Therefore, the ship owners are required to spend an increased amount of money on the routine repair and maintenance of the older ships, making them costlier to operate. The repair and maintenance costs are high especially during the fourth and fifth special surveys of the ships. The special surveys are carried out every fifth year of operation for renewing the class certificate of the ship. It includes in and out-of-water inspection of the ship’s hull to verify its structural integrity and conformance of ship’s systems, machinery and equipment with the applicable class rules (IACS, 2011). This docking is usually expensive both in costs and foregone income. The phenomenon of deterioration of a ship’s hull and/or machinery to such an extent that it becomes unworthy of repair is called as *physical obsolescence* (Buxton, 1991).

b) Technical obsolescence

The *technical obsolescence* is indicated by a ship, which, despite being physically sound, is no longer profitable to remain in service due to increased competitiveness by a more efficient ship type. As a result, such ships are likely to be scrapped. For example, three Batillus class VLCCs (550,000 T deadweight) were scrapped in the mid-1980s at the age of 7-10 years due to the lack of route and trade flexibility available in the smaller vessels, amidst the reduction of parcel sizes well below their maximum capacities due to the fragmentation of crude oil supplies (Buxton, 1991). Similarly, the tankers powered by inefficient steam turbines were gradually replaced by the ships powered by fuel-efficient diesel engines by the 1980s (Buxton, 1991, Stopford, 2009). Some ship owners of container ships even resorted to retrofit the 1970s built container ships with the diesel engines to replace the steam turbines (Evans, 1989). The scrapping of multi-deckers in the late 1960s due to the containerization is also an eminent example of technical obsolescence (Stopford, 2009).

c) Regulatory obsolescence

The scrapping of ships due to the regulatory requirements can be defined as *regulatory obsolescence*. For example, a phase-out schedule for single-hull tankers entered into force in 2005 as amendments to Annex 1 of the MARPOL convention (IMO, 2016). It was enforced after a series of accidents involving tankers leading to massive oil-spills resulting in irreparable environmental damage, to reduce the risk of oil spills from tankers involved in low energy collisions or groundings. It required the tankers of single-hull construction to phase out or convert to a double hull by a proposed deadline based on their year of delivery. The schedule decided by International Maritime Organization (IMO) ensured that all single-hull tankers were phased out by the end of 2010.

Port state controls, vetting inspections, statutory surveys, etc. are other such regulatory issues that affect the supply of ships in the demolition market. These issues force ship owners to decide on whether to invest in the maintenance and continue operating a ship or to sell it either for scrapping or in the second-hand market (EC, 2004).

2.1.1.2 Current earnings and Market expectations

Beside the above mentioned clear indicators of low earnings, the market itself can also be depressed. Therefore, the current earnings and future market expectations are two important factors, based on which ship owners decide whether or not continue trading a vessel in the shipping market. The low earnings either due to high operating costs or due to low freight rates cause a decline in the profitability of running a vessel. This dictates a ship owner to put certain cost-cutting measures in place. For example, slow steaming, laying up ships for a certain period of time, converting ships to suit alternative trades, etc. After exhausting all cost-cutting measures, a ship owner is left with two main options; one, continue to operate in the market incurring losses, expecting freight rates to improve in the near future, and two, sell either in the second-hand market for continued trading by another owner or in the ship recycling market for dismantling and recycling (Buxton, 1991).

Figure 2.1: Baltic Dry Index from Sep 2014 till Aug 2016 (Chart courtesy of StockCharts.com (2016))

A ship owner's decision to continue operating the unprofitable ship during a recession, based on his expectations of higher freight rates in future may be justified because the earnings during a freight rate boom are so great that they can overcome the loss incurred by operating in the market experiencing a slump in freight rates (Stopford, 2009). The ship owner's expectations of lower freight rates for a long period of time may force him to sell his ship. The decision to select the recycling market over the second-hand market to sell a ship is based on its saleability and market value in the second-hand market. When either the scrap value is more than the market value or there is no buyer in the second-hand market, the ship is likely to be sold in the recycling market (Stopford, 2009).

A low freight rate scenario can be seen during the times of high supply and low demand of ships for transportation. A large supply of ships than required by the market always creates pressure on the freight rates. The continued imbalance between the demand and supply of ships brings the freight rates down to such low levels that ship owners cannot operate their ships profitably and resort to scrap the old ships. This was recently observed in the dry bulk market. During the period from Nov 2014 to Jun 2015, Baltic Dry Index (BDI), representing the bulker freight rates, declined continuously from the levels of 1450 to about 580 (Figure 2.1), which led to a record ship breaking activity of 10.9 million deadweight tonnes in the second quarter of 2015 (Clarksons, 2016). Similarly, continued depressed levels of BDI from a high of 1200 in Aug 2015 to a low of 290 in Feb 2016 (Figure 2.1) led to an extensive ship demolition of about 10.1 million deadweight tonnes in the first three months of 2016 (Clarksons, 2016). The continued demolition of bulk carriers in 2015 and 2016 led to a reduction in the average scrapping age for bulk carriers from 33 years in 2007 to 24 years so far in 2016 (Clarksons, 2016).

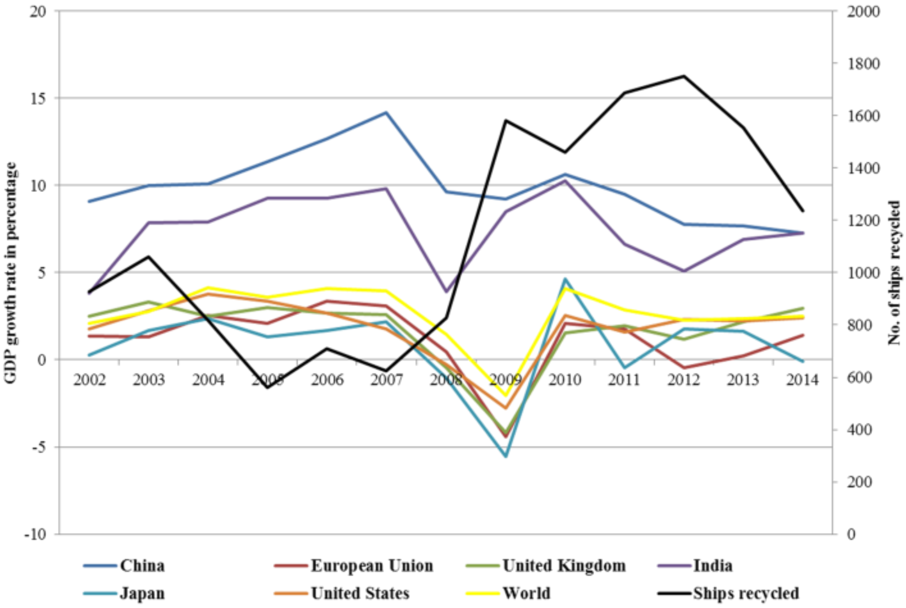


Figure 2.2: GDP growth rates of various countries and the world versus the total number of ships above 100 gross tonnage recycled globally (based on the data from World Bank and The Ship Builders' Association of Japan)

The scenario of the large-scale scrapping of ships can be seen during the times of recession when the economic growth rate is low. In such a scenario, the demand of ships for maritime transportation is low because it is a derived demand and depends largely on the amount of cargo required to be transported, which is affected by the economic growth rate. This means that during a low GDP growth rate, a less amount of cargo is available for transportation. Therefore, a less number of ships are required. In such a scenario, more and more ships are available for recycling due to an imbalance created between the demand and the supply of the ships for transportation. This is clear from Figure 2.2 which depicts the number of ships recycled every year from 2002 to 2014 superimposed with the GDP growth rates of various countries and world. The most notable point on the graph (Figure 2.2) is 2009 when the world GDP growth rate was negative and the number of ships recycled touched the 1600 mark, which was a record at that time. This record was later surpassed in 2012 due to continued low levels of freight rates and GDP growth rates across the ship types and the countries, respectively. The high amount of ship recycling activity seen in 2009 is partly attributed to the regulatory obsolescence.

2.1.1.3 Scrap prices

Scrap prices play not so important role in the ship owner's decision on when to scrap a vessel as much as in a decision on where to scrap a vessel (EC, 2004). The most important driver, as discussed before, is the operational cost of a vessel at the given level of the freight rates. A ship operating unprofitably with no expectation to be profitable in the near future is likely to end up in a ship recycling yard for scrapping even at a low scrap price. However, the decision of scrapping a ship can be delayed slightly if an increase in the scrap prices is anticipated in a short term. A ship recycling yard offering a high price for buying an EOL ship is always attractive to the ship owners. The offer price of an EOL ship depends on several global, local and other factors.

The most basic economic concepts of supply and demand form the *global factors* affecting the offer price of EOL ships. In the ship demolition market, the supply of obsolete ships is influenced by the decision of ship owners to scrap their ships whereas the demand is mainly influenced by the demand for scrap steel in the steel making industry (Kagkarakis et al., 2016, Sujauddin et al., 2016). The high supply of obsolete ships in the demolition market coupled with a low demand for scrap steel lowers the offer price while a low supply of ships during a high demand for scrap steel results in a high offer price (Jain et al., 2016b). However, there is a limit to which the offer price responds to the supply and demand forces of the ship demolition market because the demand for EOL ships is an indirect demand which is created due to the demand for scrap steel in steel making industry.

The global ship recycling yards are just one source of scrap steel which contribute only about 1.5% of the global needs of the steel making industry for scrap steel (Mikelis, 2013b). The demand for scrap steel is also fulfilled by other sources such as EOL vehicles, construction waste, other obsolete products, scrap generated at steel mills and factories producing finished goods. Therefore, due to its relatively small quantity compared to other sources of scrap steel, the scrap steel from ship recycling yards cannot dictate scrap steel pricing. Hence, the offer price to buy an EOL ship is much more influenced by the price of scrap steel in the market rather than by the demand and supply dynamics of the ship demolition market, as also demonstrated by Kagkarakis et al. (2016) in a research on forecasting the scrap price of EOL ships.

The *local factors* influencing the offer price of EOL ships include health, safety and environmental standards of a ship recycling yard, end use of scrap steel (melting or re-rolling), demand for other recyclable items (non-ferrous scrap, used machinery, furniture, etc.) in the market, labour wages, waste disposal costs, taxes and recycling method employed (beaching, slipway, alongside, drydock) (EC, 2004, Jain et al., 2016b, Sarraf, 2010).

The *other factors* affecting the offer price are distance between the last port of call of the ship and the recycling yard, contractual terms and conditions such as ‘on delivery’ and ‘as-is, where-is’, hull configuration in terms of complexity, ship's compatibility with the recycling yard in terms of size and draft restrictions, and items remaining on board such as bunkers, waste oil, spares, et cetera (Jain et al., 2016b).

The current average offer prices (Mar 2017) as obtained by GMS (2017) are in the range of 320 $/LDT for the Indian sub-continent while for China and Turkey they are about 270 $/LDT and 210 $/LDT, respectively. The difference between the offer prices of green and non-green yards is analysed in Chapter 8 based on the model developed in Chapter 6.

2.1.2 Where are ships recycled and in what quantity?

The ship recycling industry has historically been a mobile industry. It has witnessed a geographical shift through time in the quest for low labour costs and high regional demand for scrap steel (Kagkarakis et al., 2016).

The industry was initially established in the highly industrialized countries such as United Kingdom, United States and Japan when the damaged ships were dismantled after the Second World War (Kagkarakis et al., 2016, Stopford, 2009). Subsequently, it moved to Mediterranean countries such as Spain and Turkey due to stringent labour safety rules and environment protection laws (Kagkarakis et al., 2016, Sujauddin et al., 2015). Japan remained a major player till the early 1990s (SAJ, 2009).

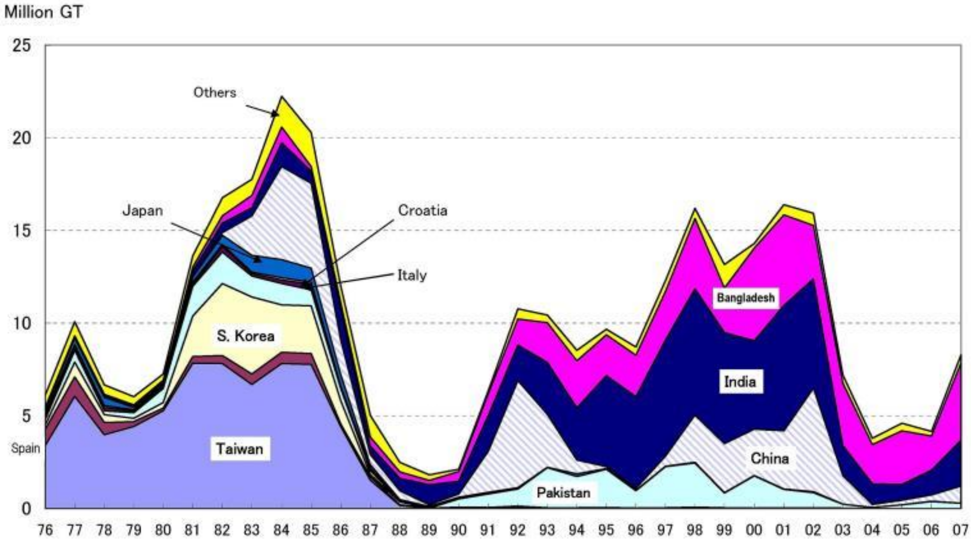


Figure 2.3: Growth of ship recycling industry from 1976 to 2007 in various countries in terms of million GT of ships recycled (Source: The Shipbuilder's Association of Japan (SAJ, 2009))

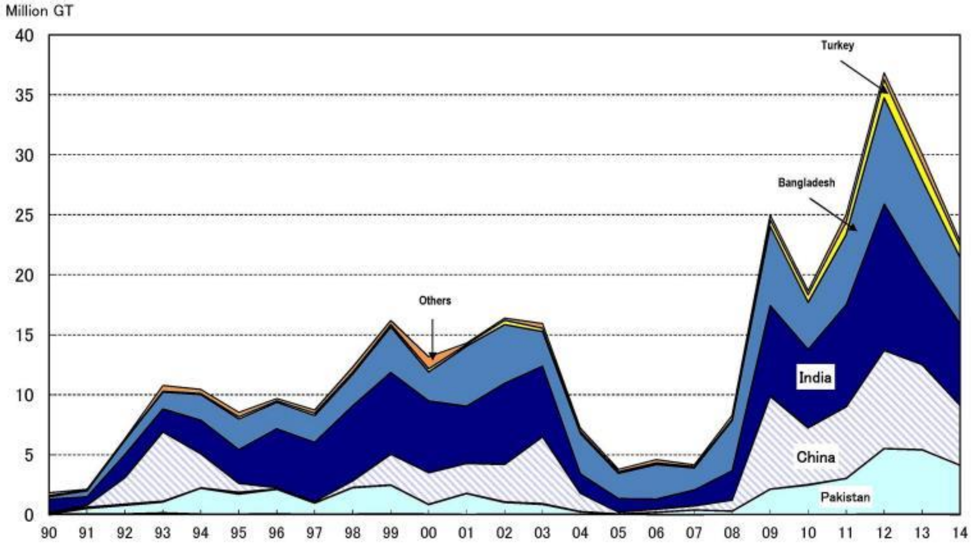


Figure 2.4: Growth of ship recycling industry from 1990 to 2014 in various countries in terms of million GT of ships recycled (Source: The Shipbuilder's Association of Japan (SAJ, 2016))

In the 1970s, the ship recycling industry started moving to Asian countries such as Taiwan, China and South Korea. By the mid-1980s, when scrapping was very high, the industry in these countries peaked with almost three-quarters of the global ship breaking business acquired by them (Stopford, 2009). Although China and South Korea entered the ship breaking business later than Taiwan (in the early 1980s), they quickly became leading buyers of EOL ships for scrap (by the mid-1980s) (SAJ, 2009).

The decline of industry in South Korea started in the late 1980s (Figure 2.3) when the wages rose and the ship building industry expanded. At the same time, as the economy grew and labour costs increased in Taiwan, the industry became unattractive and most yards were closed by the early 1990s. China, on the other hand, continued operating the demolition yards albeit with a steady decline in the market share due to government regulations controlling currency for purchasing ships and environmental regulations (Stopford, 2009). Although its market share fell from 23% in 1986 to 9% in 1995 and 3% in 2005, it remained in top five in most years till date (SAJ, 2009, Stopford, 2009).

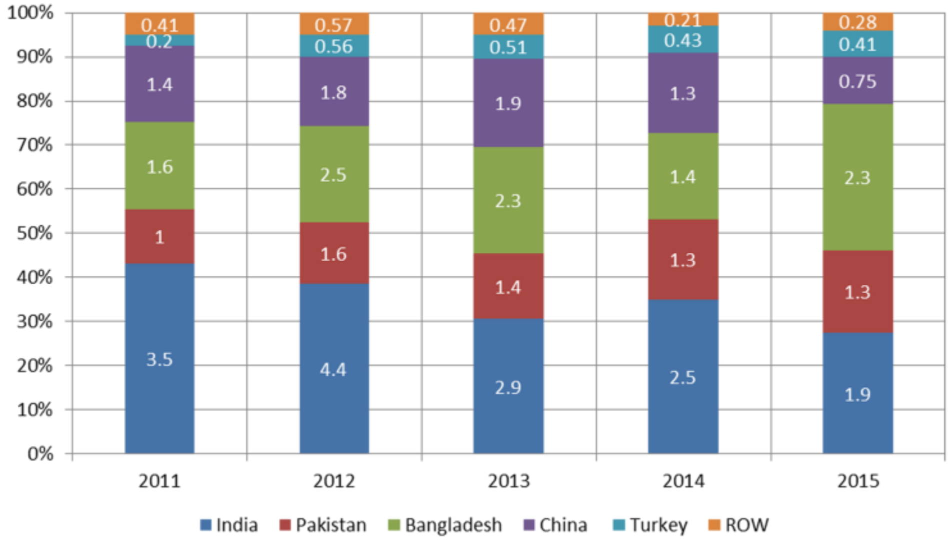


Figure 2.5: Ship recycling volumes in top 5 countries and rest of the world in terms of million T LDT and percentage of total tonnage recycled (Source: Author based on Robindesbois.org (2006-16))

The withdrawal of Taiwan, South Korea and Japan and the decline of China from the demolition business since the late 1980s to the early 1990s moved the industry gradually towards the Indian sub-continent (Figure 2.4). The sub-continent countries such as India, Pakistan and Bangladesh had a negligible market share before the 1980s but they witnessed steady growth through the 1980s and 1990s till today (SAJ, 2016). The ship recycling industry flourished greatly in these countries in the last three to three and half decades.

The growth trends of the global ship recycling industry show that since 1993, the industry is concentrated mainly in five countries, namely India, Pakistan, Bangladesh, China and Turkey (Figure 2.4). The level of activity in these ‘top-five’ countries varies from year to year and depends on the number of ships available for scrapping. They have regularly shared 97 to 98 percent of the EOL tonnage for the last 15 to 20 years (Mikelis, 2013b, SAJ, 2016). However, the fluctuations in market share of these countries are highly prominent. Turkey is the smallest of the top five recycling states in terms of the annual tonnage recycled but it recycled almost equal or more tonnage than the rest of the world in the recent past.

The last five-year trend of top five countries versus rest of the world in terms of million tonnes lightweight recycled and percentage of total tonnage recycled is shown in Figure 2.5. An interesting observation from this figure is that subcontinent countries – India, Pakistan and Bangladesh have invariably accounted for at least two-thirds of the global ship recycling activity.

The ship recycling sites in each of the five major countries are clustered in a particular region. The sites in Pakistan are mainly located near Karachi at Gadani Beach situated in Balochistan province while the sites in Bangladesh are located on the 18 km Sitakunda coastal strip situated north of the port of Chittagong. The Indian recycling sites are located in Alang in the state of Gujarat situated on the west coast while the Turkish recycling sites are located in Aliaga, a town situated on the Aegean Sea, 60 km north of Izmir port. The ship recycling in China is performed mainly in two locations – yards located along the Yangtze River in North, close to Shanghai and yards located along the Pearl River in South, in Guangdong Province. Some yards are also located close to Tianjin, North of Shanghai.

A small number of shipbreaking companies are also scattered in the UK, USA, Canada and European countries such as Spain, Belgium, The Netherlands, etc. specializing in breaking warships, fishing vessels and other high-value vessels (Abdullah et al., 2013, Kagkarakis et al., 2016, Stopford, 2009) but do not pose any competition to Asian ship breakers due to high labour costs, lack of a ready market for recycled material and stringent environmental regulations.

The size of a recycling yard is generally determined by its annual dismantling capacity, which varies from one country to another. For example, yard sizes in Indian sub-continent are in the range of 20,000 LDT to 150,000 LDT per year. The size of the yards in Turkey is in the range of 50,000 LDT to 100,000 LDT per year whereas, in China, yard sizes vary from 30,000 LDT to 1.2 million LDT per year (ClassNK, 2017, LR, 2017). In general, the yards operated in Turkey and Indian sub-continent are small to medium-sized; whereas in China, medium to large-sized yards are operated.

2.1.3 Recycling methods

Ships are recycled by employing different types of methods in different parts of the world. The methods are similar in most aspects, especially the fact that all ships are cut apart to retrieve materials for recycling, irrespective of the method of recycling employed. The major difference between various methods is the way ships are docked and the level of mechanization used to carry out the recycling process. The difference between various methods depends mainly on the location of the yard and the prevalent practices in the region.

2.1.3.1 Classification according to the way ships are docked

There are four general methods to dock ships for dismantling i.e. beaching, slipway, alongside and dry dock.

a) Beaching

Beaching is the term generally used for dismantling ships at the intertidal zone of a beach. Ships are run ashore, as far up the beach as possible, at high tide to leave them grounded at low tide (Hougee, 2013). Ships are often unable to travel as far up the beach as desired under their own power and are left stranded on the mudflats. They are then pulled higher onto the beach using chains or heavy steel wires attached to large winches on the beach (LR, 2011). As steel blocks and other equipment of a ship are progressively cut in the intertidal zone using cutting torches, ships become lighter and easy to pull up the beach by winches. Large blocks are often cut from the ship, released onto the mudflats and dragged individually by the winches onto the shore. Once on shore, everything is cut into smaller pieces as required by end buyers.

The beaching method is used to dismantle about two-third of the world’s EOL ships i.e. 66% in terms of gross tonnage (Mikelis, 2012) as well as lightweight tonnage (Figure 2.5). The main locations include Chittagong in Bangladesh, Alang in India and Gadani in Pakistan. The large tidal difference and extensive mudflats of these areas are utilized to drive ships up the beach (Lee, 2012). The beach is generally divided into ‘plots’ of about 50 meters wide and up to 100 or 150 meters deep. A major issue with dismantling ships on tidal mudflats is that any spills of oil or cargo remaining on board are likely to be swept out to sea by the next tide (LR, 2011). However, this can be avoided by taking necessary measures and following the correct procedure.

Figure 2.6: Left – Satellite image of beach at Alang, India (Source: maps.google.com), Right – A cargo ship beached at Chittagong, Bangladesh (Source: www.theguardian.com)

b) Slipway

This method is a modification of the beaching method and is also called as non-tidal beaching (LR, 2011, Mikelis, 2012). The major difference between beaching and the slipway method is that of the tide. It is practiced in areas with a low tidal difference, especially in Turkey (Hougee, 2013). Other than Aliaga in Turkey, slipway recycling is practiced in many small-scale historical recycling locations such as Inverkeithing in the UK and other locations in Europe and US today (LR, 2011). In the US slipways are generally 400 to 700 feet long (120 to 200 m) and 100 to 120 feet wide (30 to 36 m) at the entrance (USEPA, 2000). About 4% of the world’s recycling capacity uses non-tidal beaching method for ship recycling (Mikelis, 2012).

Although, in this method also, the ship is beached either against the shore or, preferably, a concrete slipway extending to the sea, an element of control is available due to the lack of tides. This means that any accidental spillages can reasonably be contained and the lifting and access operation takes place at a predictable and relatively stable waterfront (LR, 2011). Normally, the hull and machinery pieces are removed from the ship by mobile crane working from the shore as shown in Figure 2.7. It is generally acknowledged that the low tidal difference and improved access to the hull and the working area offer advantages for the safe and environmentally sound operations compared to the beaching method (Hougee, 2013).

Figure 2.7: Left – An EOL ship beached at a Turkish recycling yard on a slipway (Vardar, 2009), Right – Pictorial representation of the slipway method (Lee, 2012)

c) <u>Alongside</u>

The alongside method, also referred to as quayside, pier side or floating method, is a method to dismantle ships that are afloat and moored along wharfs, jetties or quays and/or moored offshore (Hougee, 2013). Cranes and either automated cutting gear such as mechanical shears or gas cutting torches are used to reduce the ship in a planned and structured manner. The process is 'top down' i.e. the superstructure and upper pieces are removed first, then the work continues along the ship into the engine room until only the double bottom is left (LR, 2011). This last part of the ship, an empty floating hull called the canoe, is reduced to the extent possible while afloat and then either taken out as a whole or further cut into pieces in a dry dock (Hougee, 2013). This method is mainly practiced in China, the US and Belgium.

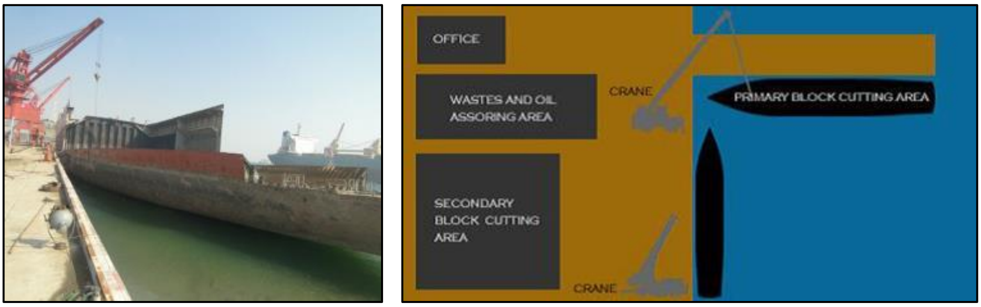


Figure 2.8: Left – A ship docked alongside for recycling (Source: Author's personal visit to a ship recycling yard in China), Right – Pictorial representation of the alongside method (Lee, 2012)

During alongside recycling, the local impact of any pollution is likely to be increased since there is no tidal dispersal effect. However, this means that concentrations can be properly monitored, contained and cleaned if necessary (LR, 2011).

d) Drydock

In this method ships are dismantled at a dry-dock, floating dock or a slipway which has a lock gate and an impermeable floor structure (Hougee, 2013). This method is the safest and cleanest way of recycling a ship because chances of polluting surrounding waters by accident are virtually nil as everything is contained within the dock (Lee, 2012). The dock is cleaned before it is flooded for dismantling the next ship in order to avoid accumulations of contaminants (LR, 2011).

Figure 2.9: Ship dismantling in drydock (Source: www.harland-wolff.com, Image reproduced with permission of Harland and Wolff Heavy Industries Ltd., Belfast, Northern Ireland, UK)

The only downside of this method is that it is the most costly method of recycling a ship which makes it most scarcely used. In 2011, Leavesley International’s facility in Liverpool was reportedly the one of the main drydock recycling locations in the UK (LR, 2011). Currently, Able UK Limited, Harland and Wolff Heavy Industries Limited (Figure 2.9) and Swansea Drydock Limited are reportedly using the drydock recycling method in the UK (EC, 2016).

2.1.3.2 Classification according to the level of mechanization

The classification of recycling methods as per the level of mechanization can be carried out into the non-mechanized process, the highly mechanized process and the intermediate process (Dev, 2010).

a) The non-mechanized process

This type of process is generally used in the Indian sub-continent yards. It uses a large amount of workforce and a bare minimum mechanical equipment to carry out the recycling process. It thrives in places where abundant cheap labour is available and low level of economic development hinders the use of capital intensive mechanical equipment and infrastructure such as slipways, jetties, waste collection and treatment technologies, etcetera (Dev, 2010). The lack of health, safety and environmental regulations also encourage this type of process.

The recycling process begins with the beaching of the ship and pulling it on the ‘plot’ using winches. The ship is then taken over by a team of labourers who carry out the cutting operation using the oxy-acetylene blowtorches. Before, starting the cutting process, they also carry out the cleaning of the ship’s tanks containing fuel oil, diesel oil, sludge, etc. and ship’s hull by removing insulation, machinery, loose items such as furniture, etc. without much use of mechanical means. The cleaning of ship tanks and hull sometimes takes place without even using the protective gears such as helmets, gloves, safety shoes, overalls, etc. while the lifting operations are carried out by bare-handed labourers (Dev, 2010).

b) The highly mechanized process

This type of process is generally found implemented in European ship recycling yards. It uses very little labour force. It thrives in places where labour is expensive and health, safety and environmental regulations are in place. The dismantling process takes place either alongside or in a drydock for a greater control of the entire operation. The cutting operation is carried out using mechanical shears. The use of blowtorches is restricted to cutting jobs which are not possible to carry out using mechanical means. The lifting and transferring of large blocks, machinery and other loose items to the secondary cutting area on the pier is carried out using the quayside gantry cranes. The ship’s hull and tanks are cleaned by using proper equipment and taking required safety precautions. The dismantling process is interrupted whenever required to achieve safe and environmentally sound operation. The process is environmentally and socially reliable because it uses standardized work practices and equipment which are able to control human and environmental risks (Dev, 2010).

c) The intermediate process

This type of process is generally used in the ship recycling yards located in China, Turkey and even at some facilities in the US (Dev, 2010). It uses both labour and mechanical equipment for the dismantling process. Although the cutting operation is generally carried out using gas torches, the lifting operations are carried out using cranes. This prevents the harsh working conditions for the workers. The use of infrastructure such as slipways, floating docks, quays, etc. provides a reasonable control over the recycling process, which ensures better safety of the workers and the environment.

2.1.4 Business details

2.1.4.1 Ship owner's perspective

Once a ship owner decides to recycle a ship, the standard procedure is to choose one of the two strategies, either sell the ship directly to a ship recycling yard or sell it through a cash buyer. Most ship owners prefer to choose the latter strategy because cash buyers pay a lump sum to the ship owners in cash in advance, and charge about 3% commission to close the deal (Engels, 2013). The cash buyers are important intermediaries forming a link between the ship owners and the ship recyclers. As they negotiate the price with the owner, they generally negotiate with several recycling yards at the same time. In some cases, they buy a ship without negotiating a firm deal with a yard. In any case, they bear all the financial risk since they sign a contract and pay the owner till they get paid for delivering a ship to a recycling yard (Krishnaraj, 2015, LR, 2011). Therefore, about 80% of the transactions follow the cash buyer route (Alcaidea et al., 2016) as it provides ship owners a sense of financial security, contrary to the distress of settling a deal with a letter of credit while selling a ship directly to a ship recycling yard (Engels, 2013). The price offered to a ship owner is always in terms of $ per light displacement tonnes (LDT).

The cash buyers purchase obsolete ships from the ship owners on one of the two conditions, either "as is where is" or "on delivery" (Jain et al., 2016b). With the "as is where is" contract, the cash buyer takes over the ownership of the ship from its last port of call till it reaches the ship recycling yard. In this case, the cash buyer usually changes the crew, re-flags the ship and subsequently delivers the ship at his risk to the recycling yard (Engels, 2013). In the case of "on delivery" contract, the ship owner is responsible for the delivery of the ship to the recycling yard in lieu of the guidance from the cash buyer on the best available market rate for the given specifications of the ship (Engels, 2013).

The approach of selling an EOL ship directly to a recycling yard may not always deliver the best results for a ship owner. It is firstly because ship owners lack the specific knowledge of the ship recycling market as they do not sell obsolete ships quite often and secondly because not many recycling yards buy ships directly from the ship owners (Ahuja, 2012, Engels, 2013). More importantly, most deals with a ship recycling yard involve a letter of credit as a payment instrument, which is not preferred by ship owners as they seek quick cash for disposing of the EOL ships.

In either case, whether a ship is sold directly to a recycling yard or through a cash buyer, more often than not a ship broker acts on behalf of the ship owner to negotiate the deal and to manage the business transaction. Shipbrokers are different from cash buyers in their mode of operations as they work directly on behalf of the ship owner and negotiate with cash buyers or ship recycling yards to find the best price for the owner (Krishnaraj, 2015). It is customary for ship brokers and cash buyers to use their own contracts when dealing with ship owners selling vessels for demolition. However, BIMCO, the largest international association of ship owners provides a standard contract for sale and purchase of ships for demolition. It is called as DEMOLISHCON (BIMCO, 2016).

In recent years, there is a growing trend among ship owners to use the services of so-called ship recycling consultants, which are companies specialising in monitoring the entire process of ship recycling from the time ship reaches the recycling yard till it is completely dismantled. They act on behalf of ship owners to ensure that a ship recycling yard follows procedures accepted by international regulations governing the ship recycling industry and relevant health, safety and environmental standards. The use of ship recycling consultants allows ship owning companies to ensure that their Corporate Social Responsibility (CSR) is well implemented.

2.1.4.2 Ship recycler’s perspective

As far as business details of a ship recycling yard are concerned, it is important to understand the cost and revenue generating factors of recycling a ship. Beside fixed capital costs and cost of purchasing a ship, a ship recycling yard must pay variable costs like taxes, government duties, premises rent, labour costs, cost of consumables including electricity, waste disposal costs for both hazardous and non-hazardous waste generated in the dismantling process, and so forth (Sarraf, 2010).

The revenue generated by a ship recycling yard depends on what types of materials can be extracted from a ship and out of those extracted, what and how much can be classified and sold as recyclable material and reusable material. Such classification mainly depends on applicable local and international regulations and local market for reusable goods and scrap metals such as steel, non-ferrous metals, etc.

The market for reusable goods and scrap products differ from one country to another. In the advanced European countries, steel scrap is generally completely melted down to make new steel products whereas in the Far East and Indian subcontinent, steel scrap is sometimes simply heated and rerolled in reinforcing rods for use in construction industry including sewage projects, metal roads and agriculture projects (Stopford, 2009, Sujauddin et al., 2016). In such countries, there is also a very strong demand for equipment and items reclaimed from ships. It includes diesel engines, generators, air compressors, deck cranes, compasses, clocks and even furniture. They are generally refurbished by specialised firms and sold to other shore-based industries and interested buyers (Rahman and Mayer, 2015).

2.2 Regulatory overview

As already mentioned above, ship recycling is considered as one of the most dangerous jobs in the world due to a very high rate of accidents and diseases, compared to other industries (Graham-Rowe, 2004). It also has consistently moved to countries where health and safety regulations are minimal. The governments, non-governmental organizations and other international organizations around the world have been putting-in their efforts to tackle the social and environmental hazards of the ship recycling industry by means of developing and implementing policies and legal instruments to govern the ship recycling industry on a global level. The relevant international legal regimes governing the global ship recycling industry are discussed below.

2.2.1 Basel Convention

The ‘Basel Convention on the Transboundary Movements of Hazardous Wastes and their Disposal’, hereinafter called as Basel Convention, was adopted in 1989 and came into force in 1992. It is an international convention that was formed to control the movement of hazardous wastes from the developed countries to the developing countries, so that the illegal dumping of wastes by the operating companies can be prevented (BC, 2011b). A follow-up legislation to this convention is the ‘Ban Amendment’. It prohibits the transportation of wastes from an OECD country to a non-OECD country (BC, 2011a). Although this amendment has not come into force, several countries including all the EU countries have ratified it (LR, 2011). The legal position of the Basel Convention and the Ban

Amendment at the European level is effectively implemented by the European Waste Shipment Regulations (EWSR) (LR, 2011, Mudgal et al., 2010).

The applicability of the Basel Convention to ships sent for recycling is resting upon three elements – first, the ships have to be classified as waste; second, they have to be subject to transboundary movement; and third, both the state of export and the state of import have to be parties to the Basel Convention (Engels, 2013). As 179 states including all member states of the European Union as well as all the major recycling states are party to the Basel Convention and transboundary movement of a ship is self-evident in its sale and purchase transaction, the only remaining question to answer is whether an EOL qualifies as 'waste' or not. Bhattacharjee (2009), Engels (2013), Moen (2008) and several others have extensively discussed the fact that the Basel Convention considers an EOL ship which is meant for export and contains hazardous materials in its structure as 'hazardous waste'.

However, due to the global nature of the shipping industry and the practices associated with sending EOL ships for recycling, there has been difficulty in applying the provisions of the Basel Convention to ship recycling and often ship owners are found to circumvent the Convention (BC, 2011b, Bhattacharjee, 2009). Two of the major hurdles to the effective application of the Basel Convention are the challenges in identifying in practice when a ship becomes waste, and identifying which country is to be regarded as the "State of export" under the Basel Convention (Bhattacharjee, 2009). These difficulties in the implementation of the Basel Convention culminated the need for a separate mandatory international regime, specifically designed to meet the unique requirements of the global ship recycling industry, and thus led to the development of the Hong Kong Convention at the IMO.

2.2.2 Hong Kong Convention

The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, commonly known as the Hong Kong Convention (HKC), was adopted at a diplomatic conference held in Hong Kong in May 2009 (IMO, 2009). However, it is not yet in force; till date, only four countries – Belgium, France, Congo and Norway have acceded to the Convention. Recently, the Danish, Panamanian and Turkish governments took necessary legal steps to accede to the Convention (DSA, 2016, Green4sea, 2017). The accession by Panama and Turkey would be a big step for the Convention to come into force as per the conditions set out by IMO for its entry into force.

2.2.2.1 Entry into force criteria

The requirements for its entry into force, as per the Article 17 of the Convention, include the following (IMO, 2009).

"The Convention shall enter into force 24 months after the date on which the following conditions are met:

a. not less than 15 States have either signed it without reservation as to ratification, acceptance or approval, or have deposited the requisite instrument of ratification, acceptance, approval or accession in accordance with Article 16;
b. the combined merchant fleets of the States mentioned in paragraph (a) constitute not less than 40 per cent of the gross tonnage of the world's merchant shipping; and
c. the combined maximum annual ship recycling volume of the States mentioned in paragraph (a) during the preceding 10 years constitutes not less than 3 per cent of the gross tonnage of the combined merchant shipping of the same States."

These requirements effectively mean that apart from the major shipping states with flags of convenience (Panama, Liberia, Marshall Islands, etc.), ratifications by at least two of the three main recycling countries (India, Bangladesh, China) are required for the Convention to be applicable (Ormond, 2012). The slow progress of the HKC towards attaining its entry into force criteria has created a skepticism amongst the stakeholders about the convention's entry into force in the near future (Cameron-Dow, 2013).

2.2.2.2 Applicability

The HKC adopts the approach of dual application covering both the ship and the ship recycling facility, which is a comprehensive approach to deal with the problems relating to human health, safety and environmental protection associated with the process of ship recycling (Jain et al., 2013). The definition of a 'ship', as given in the Convention, explicitly includes submersibles, floating crafts, floating platforms, among other offshore and storage vessels including vessel being towed or stripped of equipment. The HKC exempts ships less than 500 GT, ships operating throughout their life only in waters of the state whose flag they are entitled to fly (inland waterway vessels), the warships, naval auxiliaries and other ships not used for commercial purposes from the scope of its application. It defines the ship recycling facility as an area that is a site, yard or facility used for the recycling of ships.

2.2.2.3 Key elements and procedures

The aim of the HKC is to ensure that the ships recycled at the end of their operational lives do not pose any unnecessary risk to human health and safety or to the environment. The structure of the Convention is depicted by Figure 2.10. It contains 21 articles setting out the general legal provisions and working mechanisms, and an annex containing 25 regulations and 7 appendices, forming the essential requirements and technical details of the Convention (IMO, 2009). The regulations are divided into four chapters i.e. general provisions (Regulation 1-3), requirements for ships (Regulation 4-14), requirements for ship recycling facilities (Regulation 15-23), and reporting requirements (Regulation 24-25). The appendices contain a list of hazardous materials and a range of forms and checklists, which are supposed to facilitate compliance with the provisions of the Convention (Jain et al., 2013, Ormond, 2012).

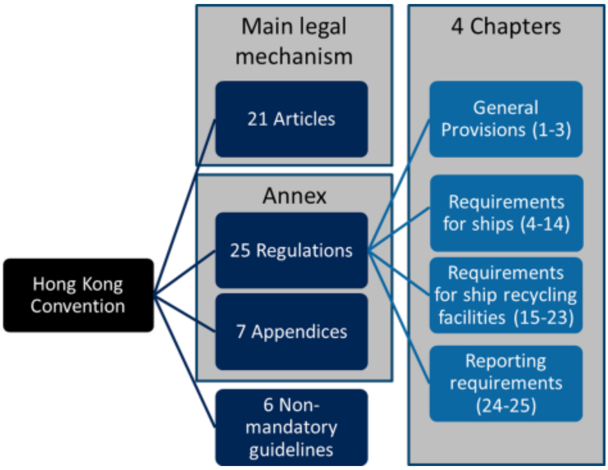


Figure 2.10: Structure of the Hong Kong Convention

It is supplemented by a set of following six guidelines:

a. Guidelines for the Development of the Ship Recycling Plan (Annex 2) (IMO, 2011b),
b. Guidelines for the Development of the Inventory of Hazardous Materials (Annex 3) (IMO, 2011a),
c. Guidelines for Safe and Environmentally Sound Ship Recycling (Annex 4) (IMO, 2012a),

d. Guidelines for the Authorization of Ship Recycling Facilities (Annex 5) (IMO, 2012b),
e. Guidelines for the Survey and Certification of Ships under the Hong Kong Convention (IMO, 2012d), and
f. Guidelines for the Inspection of Ships under the Hong Kong Convention (IMO, 2012c).

These guidelines are designed for proper implementation of the requirements of the HKC unlike other existing non-mandatory guidelines related to ship recycling developed by ILO, IMO and the Basel Convention.

The HKC, whenever enforced, will create certain obligations for various stakeholders including ship owners, ship recycling yards, Flag States, Recycling States, Port States, etc. as shown in Table 2.1. It makes mandatory for concerned ships to carry an 'Inventory of Hazardous Materials' (IHM) in accordance with its requirements. It also imposes restrictions on the installation or use of certain hazardous materials (listed in an appendix) in shipyards, ship repair yards, and ships of parties to the Convention. The IHM shall be regularly updated and certified by the Flag State using the 'International Certificate on Inventory of Hazardous Materials' (ICIHM).

Table 2.1: Impact of IMO's Hong Kong convention on various stakeholders

Recycling State	Ship Recycling Facility	Ship Owner	Flag State
• Authorize the ship recycling facility by issuing DASR. • Approve the Ship Recycling Plan. • Send a copy of the Statement of Completion to the Flag State.	• Prepare a Ship Recycling Facility Plan. • Develop a ship specific Ship Recycling Plan. • Notify the Competent Authority the planned start of recycling a ship. • Notify the CA the completion of the ship recycling by issuing the Statement of Completion.	• Always keep an IHM on board the ship. • Finalize the ship's IHM before sending it for recycling. • Provide ship related information to the ship recycling facility.	• Verify IHM, SRP and DASR.

The concerned ships are required to be sent for recycling only to the authorized ship recycling facilities. The authorization of the ship recycling facilities is subject to the inspection by the authorities of Recycling State and issuance of ‘Document of Authorisation to conduct Ship Recycling’ (DASR). The authorized recycling yards are obliged to develop a ‘Ship Recycling Facility Plan’ (SRFP) in accordance with the requirements of the Convention. They are also required to develop a ship specific ‘Ship Recycling Plan’ (SRP), specifying the manner in which each ship will be recycled. The SRP shall be developed on the basis of the ship’s IHM and other ship related relevant information provided by the ship owner. The responsibility to approve an SRP lies with the ‘Competent Authority’ (CA) appointed by the Recycling State.

The Flag State is required to issue an ‘International Ready of Recycling Certificate’ (IRRC) after verifying the ship’s IHM, DASR of the recycling facility, and the approved SRP. After the completion of recycling, the Recycling State shall issue a ‘Statement of Completion of Ship Recycling’, marking the end of the recycling process in accordance with the HKC. Subsequently, the Recycling State is required to send a copy of the statement to the ‘Administration’ which issued the IRRC for the ship. The HKC empowers the Port State inspectors to undertake investigations of the ships calling their ports to ensure the adherence to the Convention. They can even detain, dismiss or exclude a ship from their ports as a result of a violation.

2.2.3 EU ship recycling regulation

The EU regulation no. 1257/2013 on ship recycling, commonly known as EU Ship Recycling Regulation (EUSRR), was formally adopted by the European Parliament and the Council of the European Union on 20th Nov 2013. It entered into force on 30th Dec 2013, twenty days after it was published in the Official Journal of the European Union (EU, 2013). It is similar to the HKC in most aspects and does not contain any contradictory provisions that could impede the prospects of HKC getting entered into force; in fact, it is likely to support an early implementation of the HKC as this regulation is bound to be applicable by 31st Dec 2018 at the latest (EU, 2013, Mikelis, 2013a). However, few of its requirements will be applicable only by 31st Dec 2020, at the latest (EU, 2013).

Unlike HKC, EUSRR has distinct dates for its entry into force and its application. The date of application is the date after which the provisions of the EUSRR are legally applicable. The main provisions of the EUSRR are as under:

a. Its application is restricted to the ships flying the flag of a Member State of the European Union and to the vessels with non-EU flags that call at an EU port or anchorage. The ships visiting the EU ports are required to keep an IHM, prepared in accordance with its requirements. The exemptions in this regard are similar to the HKC. It also sets out responsibilities for ship owners and for recycling facilities both in the EU and in other countries.

b. The requirements for the IHM are similar to the HKC except for the inclusion of Perfluorooctane sulfonic acid (PFOS) and its derivatives in Annex I and Brominated Flame Retardant (HBCDD) in Annex II of the list of the hazardous materials (EU, 2013, Mikelis, 2013a). Annex I lists the prohibited hazardous materials whereas Annex II lists the hazardous materials which must be included in the IHM.

c. Other requirements related to the SRP, the SRFP, certification (IHM certificate and ready-for-recycling certificate), statement of completion, etc. are similar to the HKC, except that the approved recycling facilities (both EU and non-EU) will be included in the "European List" to be published by the European Council in the Official Journal of the European Union no later than 31st Dec 2016. In fact, first list was published on 19th Dec 2016 (EC, 2016). This list shall be the first point of reference for the ship owners of EU-flagged ships as they are obliged to recycle their ships only in an approved ship recycling yard. The list will be regularly updated to include or remove ship recycling facilities, as appropriate.

d. To get approved, recycling facilities will have to comply with the provisions of the HKC and also with the following three additional requirements (EU, 2013, Mikelis, 2013a):

    i. "operate from build structures";

    ii. demonstrate "the control of any leakage, in particular in intertidal zones";

    iii. ensure "the handling of hazardous materials, and of waste generated during the ship recycling process, only on impermeable floors with effective drainage systems".

2.3 Green ship recycling

With the development of international ship recycling regulations discussed in Section 2.2, several recycling yards around the world coined the term 'green' recycling to get distinct from other yards. In general, there is a common understanding within the industry stakeholders that recycling a ship with procedures to safeguard the environment and workers' health and safety in place can be called as green ship recycling, as discussed in the introduction and backed-up by the World Bank (Sarraf, 2010) and the European Commission (EC, 2007). However, using a set of criteria, based on the international ship recycling regulations (HKC and EUSRR), to recognize a green ship recycling yard would be a more pragmatic approach. Therefore, the following criteria, based on Chapter 3 – 'Requirements for Ship Recycling Facilities' of the HKC and Article 13 – 'Requirements necessary for ship recycling facilities to be included in the European List' of the EUSRR (EU, 2013, IMO, 2009) are identified.

For a ship recycling facility to be called 'green',

a. it should be authorized by the Competent Authority of the Recycling State to conduct the ship recycling operations;

b. it should prepare a ship recycling facility plan as per the requirements of the HKC;

c. it should operate from the built structures, as defined by the technical guidance note of the EUSRR (EU, 2016);

d. it should establish management and monitoring systems, procedures and techniques to prevent, reduce, minimize and to the extent practicable eliminate health risks to the workers concerned and to the population in the vicinity of the ship recycling facility, and adverse effects on the environment caused by ship recycling (EU, 2013, IMO, 2009), which includes:

    i. prevention of fires and explosions by ensuring safe-for-hot-work conditions are maintained and monitored throughout ship recycling;

    ii. prevention of dangerous conditions by ensuring safe-for-entry procedures are in place to maintain and monitor the atmosphere of confined and enclosed spaces on ship throughout the ship recycling;

    iii. prevention of accidents, occupational diseases, injuries, spills or emissions and other adverse effects that may harm human health and environment;

e. it should ensure safe and environmentally sound management and storage of hazardous materials and waste in accordance with the requirements of the HKC and EUSRR, i.e.

    i. containment of hazardous materials present on board during the entire process of recycling;

    ii. handling of waste and hazardous materials on impermeable floors with effective drainage system;

    iii. record keeping of the quantity of waste generated during ship recycling and its disposal at authorised waste management facilities only;

f. it should establish and maintain an emergency preparedness and response plan, and ensure rapid access of emergency response equipment such as fire-fighting vehicles, cranes, ambulances, etc. to ship and all areas of ship recycling facility;

g. it should train the workers and provide them with personal protective equipment;

h. it should record and report (if required) the incidents, accidents, occupational diseases and chronic effects causing risks (or have the potential to cause risks) to workers' safety, human health and the environment.

2.4 Concluding remarks

This chapter described the current state of the global ship recycling industry. It provides answer to the questions such as when ships are recycled, why ships are recycled, what are the locations at which ships are generally recycled and in what volumes, what methods are used to recycle ships in various countries, what are the business details of the ship recycling transactions and which international regulations govern the ship recycling industry. It also describes the impact of upcoming international regulations on various stakeholders. The criteria that can be used to identify a green ship recycling yard are also defined in this chapter. Using the detailed background formed by the introduction and this chapter, next chapter aims to find an answer to the key question *"how to decide what measures can be applied to a ship recycling yard to achieve the stated objectives of the research"*.

CHAPTER 3

IMPROVING GREEN SHIP RECYCLING: STRATEGIES[‡]

"The best way to have a good idea is to have a lot of ideas."

\- Linus Pauling (1901-1994), Chemist

[‡] This chapter is reproduced from the paper submitted for peer-review to the journal Environment Systems and Decisions (e-ISSN: 2194-5411).

The implementation of international ship recycling regulations and international standards of health, safety and environment (HSE) on a ship recycling yard improves environmental protection, occupational health and safety of the workers. However, it results in increased costs of the ship recycling process, which is detrimental for offering a high price to ship owners for buying end-of-life ships. In order to improve their competitiveness in the market, such ‘green’ recycling yards, as they are generally called, must either increase the revenue or reduce the costs of the ship recycling process. Apart from this, being regulatory compliant, such yards must also plan the recycling process systematically. This chapter aims to identify strategies that can help recycling yards achieve these objectives. The effective strategies are identified using the concept of cleaner production. It is chosen because it is a preventive environmental strategy that provides generic options to improve the financial and environmental performance of the production firms. The applied research method first establishes that the ship recycling process can be considered as a production process and then reviews each of the generic cleaner production options with respect to ship recycling.

3.1 Introduction

The current state of the global ship recycling industry is such that the ship recycling yards processing end-of-life (EOL) ships responsibly in terms of damage to the environment and occupational health and safety of the workers are unable to offer a high price to ship owners selling obsolete ships. This is mainly due to high operational costs of such ‘green’ recycling yards (Devault et al., 2016), as they are generally known in the industry (Sarraf, 2010). On the contrary, recycling yards with no or little control over health, safety and environmental (HSE) impacts of recycling operations can offer a higher price to ship owners for buying EOL ships. Most ship owners prefer to sell their EOL ships to such ‘substandard’ yards because their commercial interests are more important than HSE issues.

The only way for green recycling yards to augment their market share is to improve their competitiveness by increasing the price they can offer to buy an obsolete ship. The offer price can be increased by increasing the revenues and/or reducing the costs of the ship recycling process. They must also plan the recycling process systematically to abide by the international regulations governing the ship recycling industry as discussed extensively by Hiremath et al. (2016). In essence, three critical issues that must be tackled by green recycling yards are increasing revenue, reducing costs and improving planning of the ship recycling process. Therefore, certain strategies which can be used to achieve such objectives must be identified.

Although several strategies can be applied, a logical approach is required to identify the effective strategies. The research conducted by Alkaner et al. (2006) concluded that the “planning, control and organisation of disassembly operations is a relatively new subject” and “identification of transferrable best practices from non-maritime industries would be beneficial”. Therefore, this chapter investigates whether the concept of cleaner production (CP), which is widely used by production firms to improve their competitiveness, can be used to achieve the goals of the green ship recycling yards.

The primary reason to investigate the concept of CP for its application to ship recycling is the fact that the process of recycling a ship closely resembles a production process because it involves transformation of inputs into outputs. “It is a one-of-a-kind production system where the inputs are the ship, labour and equipment (such as cranes, gas torches, fork lifts, etc.) which are transformed into outputs (such as ferrous scrap, non-ferrous scrap, re-usable items, waste, etc.) as a result of various processes, such as pre-cutting, cutting and post-cutting”(Jain et al., 2017). The research carried out by Alkaner et al. (2006) also showed that ship recycling can be considered as a production system that supports the recovery, processing and resale of materials and components at the end of a ship’s useful life. Another reason to study the concept of CP for its applicability to ship recycling is the fact that it is found beneficial by several authors (Fresner, 1998, López-Gamero et al., 2010, Tseng et al., 2006, Cagno et al., 2005, Zeng et al., 2010) for improving the competitiveness, financial performance, environmental performance and operational efficiency of production firms.

The concept of CP is considered as a problem solving strategy that leads to the solution, rather than a solution in itself (Lee, 2001). Being a concept or general strategy, it could be applied to the ship recycling industry. Therefore, with the premises that ship recycling can be considered as a production system and CP can be applied to a production system to improve its competitiveness, this chapter examines the applicability of various CP options to ship recycling. The chapter continues with the detailed background of the cleaner production concept followed by a methodology to apply the concept to the ship recycling industry. The result is the identification of a number of main strategies that are of potential interest to increase the economic viability of green ship recycling, compared to substandard recycling.

3.2 Background and methodology

The awareness of the society regarding the environmental impact of the industrial activity started growing and spreading rapidly in the early 1960s (Cagno et al., 2005). The initial response to tackle the environmental problems arising due to the industrial activities was to control and treat pollutant emissions rather than finding ways to prevent emitting pollutants. This strategy was called as the ‘end-of-pipe’ approach (Cagno et al., 2005). With more research in the field, soon it became clear that pollution prevention is always better than control and cure (Van Berkel, 2000b), and environmental impacts must be seen from a product and process design point of view (Cagno et al., 2005). This led to the development of several approaches towards environmental management which include pollution prevention (P2), cleaner production (CP), industrial ecology (IE), life cycle assessment (LCA) and eco-design (Cagno et al., 2005, Dieleman, 2007). Out of these approaches, cleaner production is considered one of the most comprehensive, integrated, systematic and effective environmental management instrument as described in detail by Van Berkel (2000a). The reason is its flexibility to be applicable to all the processes and products, and its ability to provide solutions specific to each individual subject.

The term cleaner production was developed in 1989 by an expert working group as advice for Industry and Environment Program of United Nations Environment Program (UNEP) (Baas, 1995). It was formally adopted by UNEP in 1990 and was defined as “the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment” – and as applicable “to the processes used in any industry, to products themselves and to various services provided in society” (Larderel, 2002).

Although the formal definition of CP approves its applicability “to the processes used in any industry”, practically it finds applicability mainly to manufacturing/production or service companies (Dodić et al., 2010). Glavič and Lukman (2007) further limit its applicability to production activities only, as they define CP as “a systematically organized approach to production activities, which has positive effects on the environment”. According to Baas (1995), “it is a conceptual and procedural approach to production that fulfils the objective of prevention or the minimization of risks to humans and the environment during all phases of the lifecycle of a product or of a process”.

The CP concept is based on the three main guiding principles, which are precaution, prevention and integration (Jackson, 2002). These principles distinguish cleaner production from other environmental management strategies. The cleaner production strategy enables production and service companies to reduce their environmental impacts and risks to human beings from toxic materials (Dieleman, 2007, Dodić et al., 2010, Lopes Silva et al., 2013). Besides this, it also helps in increasing their productivity by reducing the wastage of raw materials, energy and other resources, which in turn benefits them financially (Dodić et al., 2010, Van Berkel, 2000b). Such environmental and financial benefits certainly indicate that CP can be useful in meeting the objectives of this research.

In this chapter, an in-depth analysis is carried out to apply the CP concept to ship recycling. A two-step methodology is used to undertake such analysis. The first step is to carry out a detailed study of the concept of cleaner production and its benefits. The second step is to assess the applicability of cleaner production to ship recycling and to generate appropriate strategies to meet the objectives of this research. This second step results in providing several strategies that may be used within the context of ship recycling. Such strategies are further analysed and their usefulness to achieve the objective of this research is discussed.

3.2.1 Cleaner production concept

Cleaner production is a very broad concept that provides generic options which can be used to develop appropriate strategies (Van Berkel, 2000b). The joint global cleaner production programme established in 1994 by the United Nations Industrial Development Organization (UNIDO) and the United Nations Environment Programme (UNEP) indicates that the following generic options can be used to apply the concept of CP (UNIDO-UNEP, 2010).

a. Good housekeeping,
b. Input material change,
c. Better process control,
d. Equipment modification,
e. Technology change,
f. On-site recovery/reuse,
g. Production of useful by-products, and
h. Product modification

These options are depicted by Figure 3.1.

The generic options are classified by El-Haggar (2007) into three main categories – reduction at source, recycling, and *product modification*. The reduction of waste at source can be achieved by *good housekeeping* and process change. The change in process can be carried out by *input material change, process control, equipment modification, and technology change*. The second main category – recycling can be divided into *on-site recycling and off-site recycling* (to produce useful by-products).

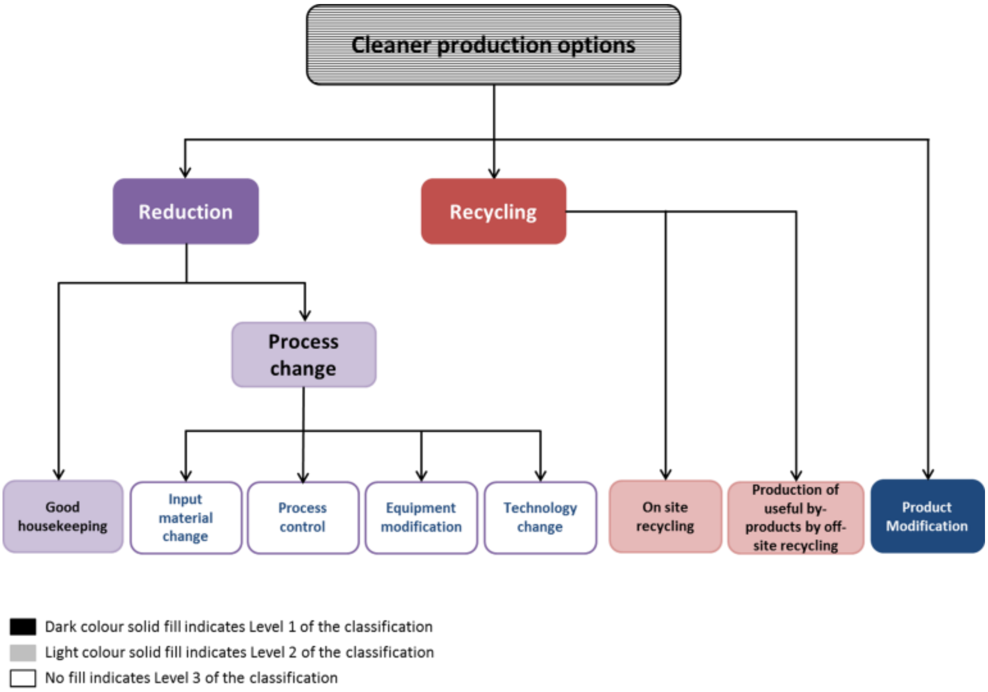


Figure 3.1: Generic cleaner production options (Source: Author based on El-Haggar (2007))

Further, UNIDO-UNEP (2010) describes that good housekeeping means keeping provisions in place to prevent leaks and spills and to achieve standardized operation and maintenance procedures and practices. The option of input material change refers to replacement of hazardous or non-renewable inputs by less hazardous or renewable materials or by materials with a longer service lifetime. The next three options, namely, better process control, equipment modification, and technology change aim to modify the production process, equipment or technology in order to minimize the waste and emission generation during production. The option of on-site recycling or on-site recovery and reuse means reusing the wasted materials in the same process or for another useful application within the enterprise. The production of useful by-products is aimed at transforming the previously discarded wastes into materials that can be reused or recycled for another application outside the company. The last option, product modification implies modifying the product characteristics to minimize the environmental impacts of the product during or after its use or to minimize the environmental impacts of its production.

3.2.2 Benefits of cleaner production

On a production firm, the main focus of cleaner production is to reduce waste generation at its source and to reduce the consumption of raw materials, energy and other resources by optimizing both the products and the processes (Severo et al., 2016). On one hand, this results in producing goods with minimum environmental impact and reduced pollution (Nilson et al., 2007); while on the other hand, it also helps in improving productivity, profitability and competitiveness of a firm (Dorfman et al., 1993, Nilson et al., 2007). These improvements are mainly due to increased savings in material costs (Van Berkel, 2000b) and waste associated operating costs (Baas, 1995, Lopes Silva et al., 2013). The optimized waste treatment, recycling and disposal due to the application of cleaner production options (Lopes Silva et al., 2013) results in reduced expenses for treatment and disposal of wastes and emissions (Van Berkel, 2000b), which further reduces the operating costs.

An incomprehensive literature survey finds several studies suggesting economic benefits of applying cleaner production to production companies in various countries such as Lithuania (Kliopova and Staniskis, 2006), Slovenia (Petek and Glaviç, 2000), Serbia (Dodić et al., 2010), Australia (Van Berkel, 2000b), Norway (Kjaerheim, 2005), India (Unnikrishnan and Hegde, 2007) and Brazil (Severo et al., 2016). The questionnaire based statistical analysis of 125 Chinese companies representing various industries (metal, heavy machinery, petroleum, chemical, pharmaceutical, paper, rubber and plastics) also showed a positive impact of cleaner production on the business performance of the companies (Zeng et al., 2010). Similarly, Cagno et al. (2005) documented the savings generated by 134 companies relating to multi-nations and multi-sectors, as a result of reduced operating costs due to the use of pollution prevention (P2) approach, an approach considered equivalent to CP (Jackson, 2002). Most economic benefits arise due to the savings in operating costs as a result of reduction in the costs of raw materials, waste disposal and pollution abatement.

The environmental benefits of applying cleaner production can definitely be seen in the form of reduced waste generation and minimized pollution of all forms including air, water, soil and noise. Fresner (1998) described how organizations can install an effective environmental management system using cleaner production. The contribution of CP in the sustainable development of modern societies (Bonilla et al., 2010) and tourism (Lee, 2001) is also well explained in the academic literature.

In addition to the economic and environmental benefits, CP can help organizations achieve other internal and external benefits (Dorfman et al., 1993, Lopes Silva et al., 2013). The internal benefits include lower absenteeism, improved productivity and personal satisfaction of workers due to improved occupational health and safety conditions (Lopes Silva et al., 2013). The external benefits include reduced liability risks, better relationships with the stakeholders, improved company image, increased market share and reduced health risks to the population in the vicinity (Lopes Silva et al., 2013).

Based on the benefits to the firms using cleaner production, as discussed in the previous section, it can be clearly inferred that the use of CP can assist in achieving the objectives of this research and improving the ship recycling industry in general. The improvement in the business and environmental performance of the production firms is mainly due to the rational use of natural resources as a result of efficient material and energy flow management (Fresner, 1998). However, in case of a ship recycling yard no natural resources or raw materials are used. Instead, an EOL ship, which is a finished product, acts as a resource. Therefore, the CP approach must be modified accordingly.

3.3 Results and discussion

3.3.1 Cleaner production in the context of ship recycling

The application of cleaner production to ship recycling can be justified by various reasons. First, the formal definition of cleaner production suggests that this approach is applicable to all industrial processes; second, the extensive use of CP in various industries for improving economic and environmental performance suggests its versatility; third, the similarity of ship recycling to a production system, a field where CP finds most applicability; and fourth, the fulfilment of objectives similar to that of this research by other industries using cleaner production.

From the perspective of a ship recycling yard, the fact that the concept of CP can be applied to a process is interesting because the recycling process affects the environment to a greater extent than the products that are created as a result of ship recycling. For green ship recycling, CP can help in reducing costs, improving revenues and planning the recycling process; while for ship recycling industry in general, it can also be useful in reducing the environmental impacts.

Cleaner production is achieved by applying expertise, improving technology and changing attitudes (Baas, 1995). However, the result or the improvement depends on the level of technology as well as on how CP is applied into everyday processes and aspects of recycling activities on a ship recycling yard. It is rightly pointed out by Jackson (2002) that developing an operational strategy on the basis of cleaner production principles is highly dependent on "sector-specific and application-specific parameters". Therefore, each one of the generic CP options discussed earlier is evaluated below for its applicability to the ship recycling industry.

3.3.1.1 Good housekeeping

The option of 'good housekeeping' is generally aimed at reducing the wastage of input materials by means of prevention of leaks and spills. In case of ship recycling, preventing the wastage of input material, i.e. ship, is not the main goal. However, prevention of spills and leaks during the ship recycling process can be useful in impeding the environmental hazards posed by dismantling of ships.

The enforcement of the HKC and EUSRR will help recycling yards to achieve good housekeeping as a result of mandatory ship recycling facility plan and ship recycling plan. It is because of the fact that SRFP (mandatory for HKC and EUSRR compliant yards) must include procedures for spill prevention, control and countermeasures to prevent inadvertent spills and leaks inflicting adverse effects on the environment (IMO, 2009, IMO, 2012a).

3.3.1.2 Input material change

The main input material for the ship recycling process is a ship. The ships sold for recycling at the end of their economic lives invariably contain one or the other hazardous material. This includes asbestos, PCB, heavy oil, sludge, ozone depleting substances, heavy metals and other similar materials. These hazardous materials, together with the complex structure of the ship pose hazards to human health and safety as well as to the environment during recycling.

Ship recycling yards can control neither the complexity of a ship nor the hazardous materials it contain. However, new ships can be built in such a way that they do not pose risks to environment, human health and safety during recycling. This concept of designing and building products that are easier and environmentally sound to recycle is called as ‘design for recycling’. It has been successfully reviewed by several researchers for applying on various products but very few have explored the possibility of applying it on ships. For example, Ferrão and Amaral (2006), Soo et al. (2015), Tian and Chen (2014) and (van Schaik and Reuter, 2004) discussed its applicability on automobiles, Durham et al. (2015) discussed its applicability on clothing, Kuo (2010) examined its usability to improve the recyclability of waste electrical and electronic equipment (WEEE), whereas Perry et al. (2012) applied the concept to composites. The studies discussing the concept in the context of ship recycling include Alkaner et al. (2006), McKenna et al. (2012) and Sivaprasad and Nandakumar (2013) before being discussed and applied on a case ship by the author in Jain et al. (2014) and Jain et al. (2016a).

3.3.1.3 Better process control

The option of better process control is aimed at modifying the production process to achieve better control on the discharges, emissions and waste generation. Its success depends on understanding and analysing the process. Therefore, a process mapping tool can be helpful in understanding the generic ship recycling process and identifying the problem areas that can be targeted not only to develop and make green ship recycling competitive but also to improve the ship recycling industry on the whole.

The objectives of this research effectuate the flow of materials on a ship recycling yard as the most critical flow of the ship recycling process. The rationale behind this is the influence of material composition of a ship on the revenue generation and the cost factors of a ship recycling project. The cost factors include the amount of resources (labour, cranes, forklifts, etc.) required to dismantle a ship, the amount of waste and its management strategy. Therefore, the material flow analysis (MFA), an analytical tool used in environmental engineering, which focuses on analysing the flow of materials within a system, is considered ideal for analysing and improving the ship recycling process. It is discussed in detail later in Chapter 5 of this dissertation.

The control of the ship recycling process is challenging because the current procedures and practices of the industry are such that the process input, i.e., a ship has a very high uncertainty in terms of the composition of the materials it contains. This makes the planning of the recycling process very difficult. The quantification of materials (Jain et al., 2016b) (Chapter 4) and the material flow analysis (Jain et al., 2017) (Chapter 5) are the first few steps towards a better control of the ship recycling process.

3.3.1.4 Equipment modification

The option of ‘equipment modification’ branches out of the option ‘process change’ and is aimed at reduction of waste at source. The underlying objective of equipment modification is to ensure production processes run at higher efficiency and lower rates of waste and emission generation. The ship recycling yards can apply this approach to modify or change the recycling equipment with more efficient and less emitting equipment. For example, yards employing oxy-acetylene gas torches for cutting the ship’s hull into smaller pieces can investigate the use of cold cutting methods such as water-jet cutting to avoid emissions of harmful gases during the cutting operation.

3.3.1.5 Technology change

The ‘technology change’ option of cleaner production is also aimed at changing the process to reduce the waste generation at source. On a ship recycling yard, generation of waste depends mainly on the downstream markets for materials/components and the costs of recovering materials/components from an EOL ship. The change in technology will not affect the amount of waste generated to a great extent except for cases where new technology can reduce the material recovery costs. More importantly, new technology such as waste-to-energy technology can be used to turn waste into new products.

The usual practice on a typical ship recycling yard for managing the waste generated by dismantling EOL ships is to contract waste management companies for eliminating the waste. This kind of waste management strategy results in expenses for the ship recycling yards. To counter such expenses, yards may use a proven waste-to-energy technology to convert waste into energy and other useful products and sell them to generate revenue. However, technical and economic feasibility of such a technology must be undertaken to decide on its applicability to a ship recycling yard. The economic feasibility analysis of the plasma gasification technology on a large ship recycling yard (annual recycling capacity of 1 million tonnes) carried out by Jain and Pruyn (2016) (Chapter 6) shows that return on such investment can become positive within 10 years of the plant operation.

3.3.1.6 On-site recovery and reuse

The ‘on-site recovery and reuse’ option of cleaner production is aimed at recycling and reusing the input material within the production process as much as possible. This option is more suitable to the production processes where there is a possibility of using waste as an input to the production process. For example, ‘own arisings’ or ‘circulating scrap’ which arise internally in steel mills as rejects from processes such as melting, casting, and rolling can be reused within the steel mill.

On a ship recycling yard, there is no waste that can be used internally within the yard processes directly. However, the ability of a ship recycling yard to convert waste into a product that is used quite a lot (e.g. energy) might be beneficial. Using a waste-to-energy plant, it can utilize this energy to run the yard equipment. A comparative analysis of benefits from selling energy and using it within the yard may still be required to take an informed decision.

3.3.1.7 Production of useful by-products

The cleaner production option of ‘production of useful by-products’ is aimed at recycling or reusing the by-products of the production process in an application outside the production plant. The by-products of an industrial process are often pollutants or they are discarded as waste. However, use of such by-products from one industrial plant by another plant supports sustainability by means of industrial symbiosis. The most famous example of such industrial symbiosis is Kalundborg Industrial Symbiosis Complex in Denmark (Jacobsen, 2006).

On a ship recycling yard, a major product that is discarded is the waste generated during the ship recycling process. The production of by-products which can be reused or recycled by other applications outside a ship recycling yard can be a useful strategy to minimize waste and prevent pollution resulting from the ship recycling process. This can be achieved by converting waste into energy and other useful products by using an advanced waste-to-energy technology.

3.3.1.8 Product modification

The last generic option of the cleaner production concept is ‘product modification’. It is aimed at minimizing the environmental impacts of a product during all phases of its lifecycle, which includes production, use, and recycling. In case of ship recycling, steel scrap is the main product which is generally used to produce new steel products either by re-processing or melting. This consumes less energy than the normal procedure of producing steel products from raw materials. Therefore, there is not much scope of reducing environmental impacts by product modification. However, this option brings a different perspective to the ship recycling industry, which is described subsequently.

A ship recycling yard generally produces two main types of products, i.e., reusable products and recyclable products. The main products of a ship recycling yard include ferrous scrap and non-ferrous scrap within the recyclable products category and items such as machinery, motors, furniture, used oil, and so on within the reusable products category. The rest of the materials obtained from the ship's hull are generally discarded as waste due to the unavailability of market demand. This includes hazardous materials such as asbestos, PCB, ozone depleting substances, etc. and other materials which cannot be sold in the downstream markets for reuse or recycling.

The types of products in demand differ from one country to other depending on the local regulations and product usability. Therefore, ship recycling yards must modify their products according to the market demand and conditions. For example, the steel (ferrous) scrap obtained from a ship can be classified into six categories, i.e., re-rollable scrap, reusable scrap, rollable scrap, bar and shape steel, solid pillar, and cast iron (Sujauddin et al., 2016).

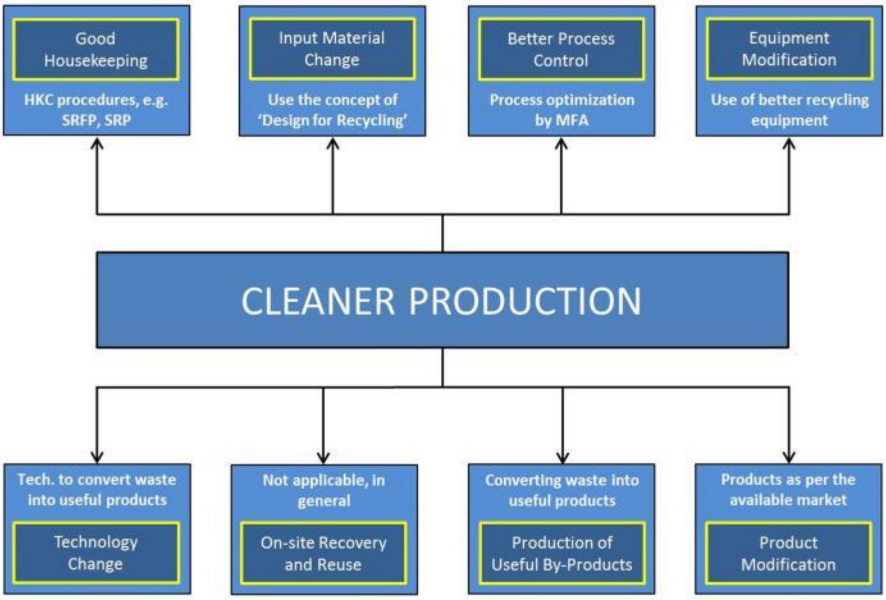


Figure 3.2: Evaluation of applicability of Cleaner Production options to ship recycling (Source: Author based on UNIDO-UNEP (2010), inner boxes describe the general CP options and outer boxes describe the applicability of each option to ship recycling)

3.3.2 Discussion

The results obtained by the evaluation of the generic cleaner production options with respect to ship recycling are summarized in Figure 3.2. The evaluation resulted in finding several strategies that are applicable to the ship recycling industry. These include the following:

1. Using the procedures of HKC such as developing a ship recycling facilities plan and ship recycling plan.
2. Using the concept of design-for-recycling for building new ships.
3. Optimizing the ship recycling process using the analytical tool – material flow analysis (MFA).
4. Using better recycling equipment to improve efficiency of the recycling process and reduce emissions and waste generation.
5. Using well established technology to convert waste generated at the ship recycling yards into useful products.
6. Producing products according to the market demand.

Most of the strategies are ship recycling yard based strategies as they are focused at bringing changes to the practices and procedures followed on a yard, except for design-for-recycling, which is a ship based strategy as it is focused at changing the way ships are designed and built. The above listed ship recycling related strategies generated by assessing the cleaner production options must be assessed for their usefulness in achieving the objectives of this research. They, as mentioned in the introduction, are to increase revenue, reduce costs and improve planning of the ship recycling process.

The results of evaluation of generic cleaner production options suggest that the objective of improving the planning of the ship recycling process can be fulfilled by implementing the procedures of the HKC, such as preparing the SRFP and SRP. However, HKC does not provide specific guidelines or a framework to prepare such plans (Hiremath et al., 2016). This procedural gap can be filled by the analytical approach proposed in this chapter, i.e., the material flow analysis. It can help recycling yards plan the ship recycling process in such a way that the costs are reduced and thus work towards fulfilling another dimension of improving their competitiveness. The use of MFA within the context of ship recycling and the role it can play in reducing the costs of the ship recycling process is explained in detail in Jain et al. (2017) (Chapter 5).

The evaluation results further suggest that the objective of increasing the revenue of the ship recycling process can be fulfilled by installing a waste-to-energy plant on the ship recycling yards so that an extra amount of earnings can be made by selling products created out of the waste. Some amount of savings can also be made due to reduced waste disposal costs by virtue of waste getting converted into energy and other useful products. The ship recycling yards can decide to offer a part of these extra earnings to ship owners in terms of improved offer price for buying EOL ships, which, in turn will make such yards attractive to ship owners. In order to draw any conclusions on the feasibility of such a technology an extensive research must be carried out. This subject is explored in Jain and Pruyn (2016) (Chapter 6), a research which discusses the economic feasibility of a plasma gasification plant on a large ship recycling yard. The impact of installing and operating such a plant on the offer price is also discussed in the same piece of research. However, a technical feasibility analysis must still be undertaken to draw some meaningful conclusions.

The evaluation results also suggest that the objective of reducing the costs of the ship recycling process can be achieved by applying the ship based strategy, design-for-recycling. This concept is aimed at building ships that contain no hazardous materials and are easy to dismantle. The improvement in ship related documents which can be useful during the ship’s recycle phase, such as weights and inventory of materials used in ship construction is also an important aspect of this concept. As discussed earlier, several studies have explored this subject. However, they are inadequate to obtain meaningful results for ship recycling, suggesting the need for further research.

The costs of the ship recycling process may also be reduced by employing certain operations management tool, for example, lean manufacturing, especially given the similarities of the ship recycling process with the production process. However, Jain et al. (2017) discussed that the unique challenges faced by the ship recycling industry make the implementation of the operations management tool rather ineffective. In spite of that, process optimization can certainly be useful. However, it depends on the willingness of the ship recycling yards to collect and analyse the relevant data. The willingness of a ship recycling yard is also required for implementing the other two yard based strategies, i.e., the use of better recycling equipment and producing market related products.

The discussion on the ship recycling related cleaner production options indicate three main strategies that are found promising to improve the competitiveness of the green ship recycling yards are:

1. Material flow analysis to improve the planning of the ship recycling process, which in turn may reduce the costs of the process.
2. Use of proven waste-to-energy (WtE) technology to valorise the waste for increasing the revenue of the ship recycling yard.
3. Designing ships using the concept of design-for-recycling to reduce their structural complexity and to limit the use of hazardous materials assisting in lowering the costs of recycling.

The implementation of both the yard based strategies (MFA and WtE) depends on quantifying the material streams originating from an EOL ship because the amount of materials to be handled by a yard must be known to analyse the flow of materials and to calculate the amount of waste generated. Therefore, a material quantification model is needed, which is presented in Chapter 4 (Jain et al., 2016b).

Table 3.1: Strategies to achieve research objectives with respect to the cleaner production options

S. No.	Cleaner Production Option	Strategy for Ship Recycling	Targeted Research Objective
1.	Better Process Control	Material Flow Analysis	Improved planning leading to reduced costs
2.	Input Material Change	Design for Recycling	Reduced costs
3.	Technology Change	Waste-to-energy Technology	Increased revenue
4.	Production of Useful By-products	Waste-to-energy Technology	Increased revenue

The ship based strategy, design-for-recycling will be able to show any improvements in the ship recycling process only 20 to 25 years after its implementation, once such ships start reaching the ship recycling yards at the end of their economic lives. Therefore, there is an urgent need to implement design related strategies. In the meantime, green recycling yards must resort to other means, such as process optimization and planning, in order to reduce the costs of the ship recycling process.

The proposed strategies in relation to generic CP options and the research objectives are summarised in Table 3.1.

3.4 Conclusion

The application of the concept of cleaner production has resulted in identifying three strategies that can be used to improve the competitiveness of the green ship recycling. These strategies are material flow analysis to improve the planning of the ship recycling process, waste-to-energy technology to improve the earnings of a ship recycling yard and design-for-recycling to reduce the costs of the ship recycling process.

The proposed strategies are classified into two categories, yard based strategies and ship based strategies. Out of the three main strategies proposed in this chapter, MFA and WtE are yard based strategies while the design-for-recycling is a ship based strategy. These strategies need an in-depth research and analysis to be able to get implemented on a ship recycling yard to improve its competitiveness. To the best of our knowledge, no other authors have undertaken the ship recycling related research on this line of reasoning. This proves the novelty and originality of this research, and at the same time, it also opens doors for other researchers to investigate the proposed strategies further.

CHAPTER 4

MATERIAL QUANTIFICATION MODEL[§]

“Exploring the unknown requires tolerating uncertainty.”

\- Brian Greene (1963 – present), Physicist

[§] This chapter is published as

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2016. Quantitative assessment of material composition of end-of-life ships using onboard documentation. *Resources, Conservation and Recycling,* 107**,** 1-9, http://dx.doi.org/10.1016/j.resconrec.2015.11.017

Minor changes are made to facilitate integration in this thesis, e.g., ‘paper’/‘article’ is changed to ‘chapter’ and square brackets are used to add new text.

The previous chapter discussed that the accurate quantification of all the material streams of an end-of-life ship is needed for planning the ship recycling process with better resource allocation and waste management strategies. This becomes more important in light of the Hong Kong convention and the new EU regulation on ship recycling. This might also assist in better estimation of cost and income of recycling the ship. Therefore, this chapter aims to develop a methodology to quantify material streams of an individual ship using the information readily available at the end of its life. The advantages of using the developed methodology are explained. Lastly, a few recommendations to improve future ship designs for safe and environmentally sound ship recycling are presented based on the knowledge gained in the methodology development process.

4.1 Introduction

Ship owners sell their end-of-life (EOL) ships to ship recycling yards either directly or through a cash buyer or broker. In some cases, even two brokers each representing the ship owner and the ship recycling yard and a cash buyer can be involved. The amount of money a ship owner gets for selling an EOL ship is determined by negotiation and depends on various factors – global, local and others.

[As discussed in Chapter 2,] Globally, the offer price is regulated by the ship demolition market depending on the supply of obsolete ships and demand for scrap metal. The supply of obsolete ships is increased during economic downturn when the demand for ships for maritime transportation is reduced, while an increased demand for scrap steel increases the demand for obsolete ships (Sarraf, 2010, Stopford, 2009). This is due to the fact that the major portion (60% to 80%) of the weight of a ship is steel (Bertram and Schneekluth, 1998). The high supply of obsolete ships in the demolition market coupled with a low demand for scrap steel lowers the offer price while a low supply of ships during a high demand for scrap steel results in a higher offer price.

[Also discussed in Chapter 2 are the facts that] Locally, factors such as health, safety and environmental standards, intended purpose of demand for scrap steel (melting or re-rolling), local demand for other recyclable items (non-ferrous scrap, used machinery, furniture etc.), labour wages and recycling method employed (beaching, slipway, alongside, drydock) plays an important role in determining the price of an EOL ship (Sarraf, 2010). For example, higher prices offered by sub-continent recycling yards as compared to those in China and Turkey is partially attributed to the availability of downstream markets formed by industrial agglomeration of ‘second-hand’ shops and re-manufacturing/re-processing/re-furbishing firms buying almost everything including ship’s machinery, motors, furniture, tanks, hardware, ancillary fittings etc. (Crang et al., 2013, Gregson et al., 2012, Hiremath et al., 2015, Rahman and Mayer, 2015) helping recyclers realise value from otherwise ‘waste’ materials of the ship. The ship recycling yards in major ship recycling nations such as India, Bangladesh, China, Pakistan and Turkey offer different prices due to such factors.

Other factors affecting the offer price include geographical position of the ship and the distance to the recycling yard, deal terms such as ‘on delivery’ and ‘as-is, where-is’, hull configuration in terms of complexity, ship’s compatibility with yard’s specifications in terms of size and draft restrictions, and items remaining on board such as bunkers, waste oil, etc.

In most cases, ship recycling yard offers a price to a ship owner on the basis of rough estimations of the amount of steel available on an EOL ship. The ship recycling yards make estimates on the basis of either experience or by an expert opinion without using any scientifically rigorous method (Misra and Mukherjee, 2009). Moreover, they do not take into account the amount of other material streams such as non-ferrous metals, machinery, hazardous materials, liquids, chemicals, gases etc. in determining the offer price.

The offer price should actually be determined on the basis of the estimation of cost and revenue generated in dismantling and recycling a ship. Although there are many factors affecting the cost and revenue of recycling a ship, type and quantity of materials plays an important role. For example, high quantity of asbestos will result in extra measures to be taken and a longer processing time resulting in higher cost for recyclers. Also, the revenue is mainly generated by selling materials such as ferrous scrap, non-ferrous scrap, machinery, equipment and other items. The material quantification of a ship is thus essential for planning the recycling yard’s operations and will help recyclers incorporate the effect of materials on the price offered to a ship owner.

The quantified material streams are essential for yards to create a robust ship recycling plan as required by not yet applicable EU regulation and Hong Kong convention on ship recycling. An enhanced ship recycling plan can be devised because the quantified material streams can be used to determine the amount of waste that would be generated in recycling an EOL ship depending upon the earning potential of each of the material streams as well as to carry out a material flow analysis (MFA). MFA, an analytical method of systematic assessment of flows of materials within a complex system defined in space and time (Brunner and Rechberger, 2004), is a tested technique which was applied in the past on specific EOL products that are potential sources of materials including EOL commercial vehicles (Mathieux and Brissaud, 2010) and short life goods such as aluminium packaging and glass (Binder and Mosler, 2007). The concept of MFA can also be applied for better waste management (Arena and Di Gregorio, 2014, Brunner and Rechberger, 2004) and sustainable development (Huang et al., 2012).

MFA has never been applied on ships except being mentioned by (Sujauddin et al., 2015) pointing to another publication of theirs (Sujauddin et al., 2012) stating this area of study remained unexplored. If MFA is applied on a ship recycling yard, it can help reduce recycling costs, improve hazardous waste management and enhance environmental performance by optimizing the recycling process in such a way that resources are allocated and utilized in the most efficient manner. MFA can help carefully plan the steps to reduce a several hundred meters long ship to small pieces suitable for re-melting furnaces by optimizing the number and size of the pieces that can be cut from a ship, the number and capacity of cranes and forklifts available to move them off the ship to processing stations elsewhere in the yard, the capacity of the processing stations to cut up and sort the metals, and the capacity of the truck loading systems so that the materials flow smoothly through the process with minimum labour and without delays. Precisely, MFA based on the quantified material streams can be used as a tool to better plan the ship recycling process for achieving cost effective, safe and environmentally sound ship recycling.

This chapter will continue further with a review of the limited literature available on the estimation of materials of the ships to be recycled. It will also briefly search for inspiration in other industries, such as vehicle and aircraft sectors. Although useful, the impact of best practices from other industries will only benefit ship recycling in 20-30 years' time (lifetime of vessels); hence the chapter will also develop a method that will use the official and thus obligatory vessel documentation to more accurately estimate the different material weights of the vessel.

4.2 Literature review

4.2.1 Comparison with other industries

It would be worthwhile to discuss why is it important to develop a methodology for material quantification of EOL ships by comparing the ship recycling industry with the aircraft and the vehicle recycling industry.

The recycling approach of the shipping industry resembles the approach used by the aircraft recycling industry. The aircraft recycling involves disassembly of reusable components and then shredding the remaining hull to obtain ferrous and non-ferrous scrap using the separation technologies (van Heerden and Curran, 2010). Similarly, the ship recycling industry is pre-dominantly based on salvaging as many components as possible having second-hand value in the market and then cutting the ship’s hull (ferrous) into plates and blocks of sizes that are readily accepted in the scrap market (Andersen et al., 2001). On the contrary, the vehicle recycling industry mainly rely on shredding the vehicle hull to obtain ferrous and non-ferrous scrap for recycling using the separation technologies because of non-existent market of reusable components (Sakai et al., 2014). Moreover, vehicle recycling industry has frequent supply of small units unlike the ship recycling industry having an intermittent supply of large units.

Though, the ship recycling industry resembles the aircraft recycling industry in following a similar recycling approach; its earning model is similar to that of the vehicle recycling industry, contrary to the earning model used by the aircraft recycling industry. It depends more on scrap value than on component value (van Heerden and Curran, 2010). This is the reason why material quantification related studies are abundantly available within the literature of vehicle recycling industry (Ferrão et al., 2006, Gerrard and Kandlikar, 2007, Jeff and Gregory, 2001, Kanari et al., 2003, Mat Saman and Blount, 2006, Vermeulen et al., 2011) while the literature of aircraft recycling industry is more focused on disassembly of reusable components (De Brito et al., 2007, Ribeiro and Gomes, 2015, van Heerden and Curran, 2010).

In conclusion, ship recycling industry is similar to both vehicle and aircraft recycling industry in certain aspects; yet the difference not only due to large size and various types of ships but also due to large age range, infrequent supply and dynamic composition of ships due to change in regulations over time makes it difficult to instantly apply the existing quantification models of other industries. The strong market presence for EOL ship’s machinery, equipment and other reusable items is similar to that of aircraft recycling while high demand for high value non-ferrous scrap such as special bronze and ferrous scrap in the form of plates and blocks in the scrap market is similar to that of vehicle recycling industry. Both these factors make it vital to quantify the material streams of an EOL ship to calculate cost and income of recycling a ship.

4.2.2 Material composition of end-of life ships

For this study, all the available research papers and technical reports on material quantification of EOL ships were reviewed. Unfortunately unlike the car and aircraft industry, the number is limited (nine only). The very small number of studies available on this subject is attributed to ship recycling yards being sceptical about sharing the information and data. The prevalent scepticism is mainly due to continuous scrutiny of recycling yards by environmental watchdogs. Other stakeholders, such as classification societies and ship recycling consultants are bound by the non-disclosure agreements of the proprietary data.

The literature review found that the studies used four different methods to quantify material streams of EOL ships. This include interviews of ship recyclers, sampling on a few ships, sampling on the beaches of a few recycling yards, and an input-output method applied at a particular recycling yard based on the approximate historical data of few ships.

While Andersen et al. (1999) aimed to quantify the materials of environmental concerns available on an EOL VLCC ship by sampling; Hiremath et al. (2015) and Sarraf (2010) attempted to quantify waste streams of various ship types on an aggregate level whereas Reddy et al. (2003) attempted to quantify the waste generated by Alang-Sosiya ship breaking yard in Gujarat, India in terms of MT/day by sampling on beach. Although all four authors (Andersen et al., 1999, Hiremath et al., 2015, Reddy et al., 2003, Sarraf, 2010) attempted to quantify only the waste streams while ignoring other material streams such as ferrous, non-ferrous, machinery etc., their studies are unfortunately not comparable due to different approach of research used by them.

The study carried out by Hiremath et al. (2015) is the most accurate of these studies because authors used a relatively large sample set of 241 ships. However, both the type of ships demolished and the materials on board vessels change over time (the first due to economic circumstances and the second due to changes in regulations). For example, International Maritime Organization (IMO) started banning asbestos by means of SOLAS convention in 2002 which was eventually banned totally for use on all installations on all ships in 2011 (LloydsRegister, 2011). This means resampling will need to be done regularly to make sure the values of emission factors remain correct. It was also noted that bilge water was assumed as part of LDT, but as it is operationally generated, it should be part of deadweight tonnage (DWT) (Eyres, 2007). Sarraf (2010) used gross tonnage (GT) to represent the ship size, which is rather impractical as GT is a measure of volume rather than a weight (Eyres, 2007). Also, Sarraf (2010) claim to have had no access to proprietary data of Inventory of Hazardous Materials (IHM) of various ships available with classification societies, making estimation difficult and inaccurate. Lastly, the results obtained by Reddy et al. (2003) are the most inaccurate ones due to calculation discrepancies and unrealistic assumptions such as only source of waste collected at Alang-Sosiya beach are ships and no extrapolation of the amount of waste found in three months to the value for one year, the value was taken as is.

The studies carried out by Adak (2013), Andersen et al. (2001), Demaria (2010), Hess et al. (2001), and Sujauddin et al. (2015) are an attempt to quantify all the material streams of EOL ships using different research ideologies. The results of these studies are compiled in Table 4.1. While Adak (2013) and Hess et al. (2001) focused on material quantification of three major ship types General cargo, Bulk carrier and Oil tanker, Demaria (2010) and Sujauddin et al. (2015) focused on ships in general. These estimates are on an aggregate level based on the experience of ship recyclers and waste disposal data published by government agencies in India and Bangladesh. They are mere approximations of the quantity of material streams of an EOL ship. Unexplained weight losses of 9% to 16% of the weight of the vessel are reported by Adak (2013) and Hess et al. (2001). This weight loss might be due to margins of error and misdeclarations. In India and Pakistan, there have been regular instances of discrepancies in declared import weight and material sold for re-rolling. This include cases where more scrap was reportedly sold than imported (Imaduddin, 2012, Krishna, 2010). The misdeclarations can be for several reasons; the material stream is either escaped to the environment (Sujauddin et al., 2015), is dumped illegally either into the sea or at nearby villages (Demaria, 2010, Upadhyay, 2002), or quite simply done for tax evasion.

The study carried out by Andersen et al. (2001) for classification society DNV is the only one that focused on individual ships (Tanker and Bulker) to calculate their material composition by sampling on a VLCC ship and using empirical estimations available in the ship design literature (Bertram and Schneekluth, 1998) to calculate the weight of machinery (W_m), outfitting (W_o) and steel (W_s). This is the most detailed and comprehensive of all the studies. Other studies on ship recycling (Koga et al., 2008) have used this data as well. The major drawback of this study is the use of data on W_m, W_o and W_s from the literature make these estimates inaccurate because this data is not up to date and the composition of ships changes over time.

Table 4.1: Amount of material streams (percentage of LDT) of end-of-life ships as obtained by reviewed studies

	(Adak, 2013)			**(Andersen et al., 2001)**		**(Demaria, 2010)**	**(Hess et al., 2001)**			**(Sujauddin et al., 2015)**
Ship types / **Material streams**	**General cargo**	**Bulk carrier**	**Oil Tanker**	**Tanker**	**Bulker**	**Ship**	**General cargo**	**Bulk carrier**	**Oil Tanker**	**Ship**
Ferrous scrap	64.50	68.50	76.50	74.40	63.15	75-85	56-70	61-71	72-81	85.00
Re melting scrap	10.00	9.00	6.00			3.00	10.00	8-10	5-7	
Cast Iron	1.75	2.00	2.50				2-5	2-3	2-3	
Non-ferrous scrap	0.75	1.00	1.25	0.07	0.12	1.00	1.00	1.00	1-2	0.40
Machinery	6.00	3.50	1.25	14.00	19.00	10-15	4-8	2-5	1-2	8.60
Electrical and electronic equipment				2.50	5.00					
Minerals				0.50	2.50					
Plastics				0.50	1.20					
Liquids, Chemicals and Gases				2.03	1.03					
Furnace oil and oils						2.00				
Joinery				5.00	6.00					
Wooden and furniture						2.00	5.00	1-5	1-2	
Miscellaneous	5.00	3.00	1.50	1.00	2.00					
Burning, cutting losses and waste						5-10				6.00
Weight loss	12.00	13.00	11.00				9-15	10-16	10-12	

In conclusion, all of these studies use aggregate data for large groups of ships, none of these studies present a methodology that can be used by recycling yards to determine the amount of various material streams of a specific ship that they are working upon. Therefore, a methodology to quantify the material streams of an EOL ship using the information available from the ship at the time of offering is presented in this chapter.

4.3 Discussion and research methodology

The methodology developed in this chapter is based on the information available to ship recycling yards when they buy an obsolete vessel from the ship owners. In the present scenario, where no international regulation on ship recycling is in place, the ship’s stability manual is the only document that is made available by a ship owner to various stakeholders of the ship recycling industry. It contains detailed ship specific information and parameters such as length, breadth, depth, displacement, deadweight and lightweight distribution. Lightweight (LDT) is a measure of ship’s weight as built without cargo, bilge water, ballast, fuel oil, stores, spares, crew and its personal effects (Eyres, 2007). It is an important parameter for a recycling yard to estimate the steel weight of the ship for calculating recycling cost and planning the recycling activities while port authorities levy import duty, customs duty and other taxes on an EOL ship per LDT basis.

The stability manual is a legal document that must always be kept on board the vessel. It is created by naval architects to help ship’s crew calculate the vessels stability in varying conditions of load to ensure safe vessel operations (Barrass and Derrett, 2011). An important aspect of ship’s stability manual is that it must be approved by the classification society with other plan approval documents at the time of building a ship. It must also be updated regularly throughout the ship’s lifetime for any changes to vessels’ main particulars including lightweight. Moreover, ship’s stability manual is required to contain certain mandatory documentation specific to each ship type (DNV, 2011). In general, contents of the stability manual must have sufficient information to enable safe and stable ship operation, it is however not standardised.

Once the Hong Kong convention (HKC) on ship recycling adopted by International Maritime Organization (IMO) in 2009 (IMO, 2009) comes into force, ship owners would be obliged to share the Inventory of Hazardous Materials (IHM) along with other ship specific information such as finished drawings of major equipment, general arrangement, engine room arrangement, piping diagrams, capacity plan, shell expansion plan, fire control plan etc. with ship recycling facilities for developing a ship recycling plan (IMO, 2011b). The convention is open for accession by any State and it will enter into force whenever its entry into force criteria is fulfilled (IMO, 2015). As major recycling nations having a large number of non-complying yards have a major influence on enforcement of the HKC (Cameron-Dow, 2013), it is expected to take quite some time before it will come into force.

Although ship specific information that would be made available post implementation of the HKC would help better plan the recycling process, it would not allow for a direct calculation of all the material weights. Hence, even if the convention comes into force, a method is still needed to quantify the material streams of an EOL ship. The lightweight distribution presented in the ship's stability manual can be used for this purpose using a two-step methodology explained below.

The lightweight distribution of the case ship, a 2006 built handymax bulk carrier, is composed of four components i.e. machinery components comprising elements M01 to M10, outfitting components comprising elements U01 to U09, steel components comprising elements S01 to S16, and the correction factor comprising element X01. The exact lightweight distribution as given in the stability manual (CarlBro, 2006) of the case ship, arranged by components, is shown in Table 4.2.

After completing the first step of arranging individual elements of the lightweight distribution of the case ship into four main components machinery, outfitting, steel and correction factor based on the codes M, U, S and X respectively given in the stability manual, the second and final step is to distribute each of the 36 elements M01 to M10, U01 to U09, S01 to S16 and X01 into various material streams.

The material streams for this distribution are derived from the DNV study (Andersen et al., 2001) as it is the most comprehensive and realistic list of material streams presented by any author in the literature. According to the DNV study, there are a total of nine material streams originating from an EOL ship as shown in Table 4.3. For easy calculations, a code is assigned to each material stream, starting from W01 to W09. The material stream W07: liquids, chemicals and gases is not a part of ship's LDT because it is usually generated operationally. Hence, it will not play a role in converting the weight elements into material streams. The operationally generated material streams make the final weight of the ship at the end of its life higher than its LDT recorded at the time of building.

Table 4.2: Lightweight distribution of the case ship as given in its stability manual

S.no.	Code	Components	Area	Weight (T)
1.	M01	Machinery components	Machinery piping	95.0
2.	M02		Electrical	25.0
3.	M03		Bridge equipment	6.0
4.	M04		Tools and Spares	15.0
5.	M05		Main Engine	220.0
6.	M06		Shafts	28.0
7.	M07		Propeller	17.0
8.	M08		Auxiliary engines	38.0
9.	M09		Machinery comp	80.0
10.	M10		Machinery equip	115.0
11.	U01	Outfitting components	Crane 1	57.0
12.	U02		Crane 2	57.0
13.	U03		Crane 3	57.0
14.	U04		Crane 4	57.0
15.	U05		Hatches	880.0
16.	U06		Outfit For	220.0
17.	U07		Outfit Mid	200.0
18.	U08		Outfit Aft	500.0
19.	U09		Paint and Cathodes	130.0
20.	S01	Steel components	Forepeak Fcle	320.0
21.	S02		Bhd CH1-CH2	182.0
22.	S03		Bhd CH2-CH3	198.0
23.	S04		Bhd CH3-CH4	198.0
24.	S05		Bhd CH4-CH5	182.0
25.	S06		Cargo Section	5600.0
26.	S07		Machinery Section	1070.0
27.	S08		Casing Funnel	80.0
28.	S09		Accommodation	320.0
29.	S10		Hatch coaming	205.0
30.	S11		Crane pedestal 1	18.0
31.	S12		Crane pedestal 2	18.0
32.	S13		Crane pedestal 3	18.0
33.	S14		Crane pedestal 4	18.0
34.	S15		Deck house Fr. 72	12.0
35.	S16		Deck house Fr. 144	12.0

36.	X01	Correction factor	Tol and Marg	-203.9
			Total LDT (tonnes) :	**11044.1**

The quantification of material streams using the methodology developed in this chapter mainly depends on the weight elements of the lightweight distribution of the ship recorded in its stability manual. Although international rules governing the general contents of the stability manual (DNV, 2011) ensure that the lightweight particulars of a ship are recorded in its stability manual, unfortunately there is no rule standardizing the elements of the lightweight distribution. These elements could be more comprehensive than the elements of the case ship or just a few elements, say steel weight, outfitting weight and machinery weight put together to calculate the final LDT. However, it is very likely that lightweight distribution of every ship would contain detailed enough weight elements similar to that of the case ship due to reasons such as (1) ship building yards usually calculate weight elements in detail using a software having standardized weight elements (2) quantification of weight elements in detail is required by ship building yards to calculate ship construction costs (3) the classification society surveyor might be interested in detailed level of weight elements for inclining experiments and approval of stability manual, and (4) it is obligatory for the manual to have sufficient details to enable master to operate the ship in compliance with the stability requirements applicable to the vessel.

Table 4.3: Material streams of an end-of-life ships

Code	Material Stream
W01	Ferrous scrap
W02	Non-ferrous scrap
W03	Machinery
W04	Electrical and electronic equipment
W05	Minerals
W06	Plastics
W07	Liquids, Chemicals and Gases
W08	Joinery
W09	Miscellaneous

4.4 Application and results

The division of each of the 36 weight elements M01 to M10, U01 to U09, S01 to S16 and X01 of the case ship into various material streams W01 to W09 is not a straight forward exercise due to unavailability of the information on what material and component formed an element of weight distribution when the ship was constructed. The division can be done on the basis of logical reasoning and empirical evidences within the ship design literature while the knowledge gaps due to unavailability of data are filled-up using the DNV study. The most plausible division of these elements into material streams is shown in Table 4.4 based on the following discussion.

Table 4.4: Division of lightweight distribution elements into material streams

S.no.	Elements	Material streams
	Machinery components	
1.	M01: Machinery piping	W01, W02
2.	M02: Electrical	W02, W04
3.	M03: Bridge equipment	W04
4.	M04: Tools and Spares	W01
5.	M05: Main Engine	W03
6.	M06: Shafts	W01
7.	M07: Propeller	W02
8.	M08: Auxiliary engines	W03
9.	M09: Machinery comp	W01, W05
10.	M10: Machinery equip	W03, W09
	Outfitting components	
11.	U01 – U04: Crane 1 - 4	W03
12.	U05: Hatches	W01
13.	U06: Outfit For	W01, W02, W03, W04, W05, W06, W08, W09
14.	U07: Outfit Mid	W01, W02, W04, W05, W06, W08, W09
15.	U08: Outfit Aft	W01, W02, W03, W04, W05, W06, W08, W09
16.	U09: Paint and Cathodes	W02, W09
	Steel components	
17.	S01 – S16: Steel hull elements	W01
	Correction factor	
18.	X01: Tol and Marg	W01

4.4.1 Steel components and correction factor

The elements of steel components S01 to S16 and correction factor X01 forms material stream ferrous scrap (W01). It is realistic to add negative component correction factor: X01 to steel components because the most likely cause of such a correction in ship’s LDT would be an error in weight estimation of steel components during the initial phase of ship design cycle. Moreover, steel components are the biggest contributing elements (over 80%) to the ship’s LDT.

4.4.2 Machinery components

The elements of machinery components M03 to M08 can be placed in different material streams without any ambiguity. Bridge equipment (M03) can be placed in material stream electrical and electronic equipment (W04); tools and spares (M04) and shafts (M06) form the material stream ferrous scrap (W01); main engine (M05) and auxiliary engines (M08) form the material stream machinery (W03); while propeller (M07) can be placed in material stream non-ferrous scrap (W02) because ship’s propeller is usually made of special type of bronze.

4.4.3 Outfitting components

Similarly, the elements of outfitting components U01 to U05 can also be placed in different material streams without any ambiguity. The elements U01 to U04 are cranes forming material stream machinery (W03) while hatches (U05) can be placed in material stream ferrous scrap (W01).

4.4.4 Remaining components

The remaining 8 elements of machinery components and outfitting components M01, M02, M09, M10, and U06 to U09 needs to be divided into two or more than two material streams. Dividing these elements into material streams needs a close examination and understanding of how the ships are designed and constructed.

4.4.4.1 Remaining machinery components

The element M01: machinery piping can be split into two material streams ferrous scrap (W01) and non-ferrous scrap (W02) because piping in the machinery room could be of either steel or copper. The weight of ferrous and non-ferrous machinery piping is not known at the time ship is sold to a recycling yard but it is certainly known when the ship is built. The transmission of this information to the recycling yard is critical in quantifying these material streams of an EOL ship. In this study, based on a personal communication to a leading classification society, Lloyds Register; it is estimated that the total weight of copper (non-ferrous) piping in the machinery room would be no more than 5% of the total piping. It is verified by the fact that most of the machinery piping is constructed of ferrous material (Murdoch, 2012). Though almost every machinery system piping can be of approved non-ferrous material such as copper, aluminium and their alloys, if used within the design rules of classification society (DNVGL, 2015); ferrous material is generally preferred due to economic considerations. The author's experience and Barrass (2004) confirms that the use of copper piping within the machinery room of a ship is limited to low temperature steam systems and pneumatic systems. The other smaller systems such as systems for compressed air, sanitary systems, bilge, ballast water, brine, hydraulic lines and tank heating also use copper-nickel alloys (CDA, 2015). Thus, an estimate of maximum 5% for non-ferrous piping seems realistic.

The element M02: electrical should logically form the material stream electrical and electronic equipment (W04) but due to the missing information on whether electrical cables were considered a part of element M02: electrical or element U06, U07, U08: outfitting during ship construction, it is assumed that the element M02 would split into two material streams; non-ferrous scrap (W02) for copper cables, and electrical and electronic equipment (W04) for the equipment. This is based on the generic information provided by ship design literature (Papanikolaou, 2014) confirming that 50% to 80% of the weight of electrical concern the weight of cables. Thus, due to relatively small size of the case ship, element M02 is divided equally into two material streams W02 and W04.

The element M09: machinery comp usually concern the weight of ladders, floor gratings, floor plates, railings, heat and noise insulation in the engine room of a ship (Bertram and Schneekluth, 1998, Papanikolaou, 2014). Such information from the ship design literature confirms the division of element M09 into two material streams i.e. ferrous scrap (W01) for ladders, floor gratings, floor plates, and railings and minerals (W05) for heat and noise insulation. The missing information on the weight of individual components comprising the element M09 is fulfilled by the DNV study on VLCC ship (Andersen et al., 1999) which estimated 7T of heat and noise insulation on a 37500 LDT tanker ship. For the case ship, the element M09 weighing 80T is split into 5T of minerals (W05) and 75T of ferrous scrap (W01). The heat and noise insulation of a ship's engine room mainly depends on its size (m^3).

The element M10: machinery equip concern all the machines and equipment in the engine room except the ones which are reported individually in the stability manual.

In the case ship, weight of main engine and auxiliary engine is reported in elements M05 and M07 respectively. This means the element M10 can be split into material streams machinery (W03) and miscellaneous (W09) accounting for level switches, thermometers and batteries. Such items are small in size but large in number. Thus, in this study, due to the missing information on the weight of individual components comprising the element M10, weight of material stream W09 originating from the element M10 is approximately considered 1T. The remaining weight of 114T is assigned to material stream W03.

4.4.4.2 Remaining outfitting components

The element U09: paint and cathodes can naturally be split into two material streams i.e. non-ferrous scrap (W02) accounting for the weight of cathodes and miscellaneous (W09) accounting for the weight of paint. The information on the individual weights of paint and cathodes is not available when a recycling yard purchases a ship for recycling but it is certainly known to the yard building the ship. The estimations made by DNV for the VLCC ship (Andersen et al., 1999) reveals that the combined weight of paint and cathodes comprises of 58% of cathode weight and 42% of paint weight. The weight of the paint is converted from litres to tonnes assuming the density of paint as 1.2 g/cu cm. On board ships, different varieties of paints are used (Almeida et al., 2007) having densities ranging from 0.9 to 1.5 g/cu cm (CMP, 2015). Using the above division, cathode weight of the case ship is estimated to be 76T while the weight of the paint is estimated at 54T forming the material streams W02 and W09 respectively. The weight of cathodes measured at the end of ship’s life depends on when the ship was last dry docked for renewal of cathodes and other repairs, as this material is ‘sacrificed’ to prevent rusting of ship’s hull (Bohnes and Richter, 1997).

The elements U06, U07 and U08 represent the weight of outfitting forward, middle and aft of ship respectively. The outfitting on a ship usually consists of various items made of different materials. Shipyards use differing schemes to denote which items are considered outfitting. The ship design literature can provide some insight regarding this topic. For example, (Bertram and Schneekluth, 1998) (pg. 169) divided outfitting into four major groups hatchway covers, loading equipment, accommodation, miscellaneous. Similarly, (Papanikolaou, 2014) (pg. 215) divided outfitting into eight groups comprising various items. Every ship yard has their own criteria to include items within the outfitting weight group. At recycling stage, it is impossible to segregate outfitting elements U06, U07, and

U08 into the material streams without having the information from the ship building yard.

In this study, outfitting elements are considered to contain all the material streams from W01 to W09 except W07: liquids, chemicals and gases which is operationally generated and is not the part of ship’s lightweight. Another exception is omission of material stream machinery (W03) originating from the element outfit mid (U07) because it is unlikely that a bulk carrier would have machinery installed at its mid area, when cranes are part of different elements (U01-U04). The outfitting elements of the lightweight distribution of the case ship are distributed into various material streams using the following logical assumptions.

The material stream ferrous scrap (W01) generated from the outfitting elements mainly comprise of stairs, ladders, railings, pipes, anchor and chain (Bertram and Schneekluth, 1998, Papanikolaou, 2014). Similar subdivision from machinery component M09 resulted in 75T of ferrous scrap stream. It is assumed that the part of the ship other than machinery space would have similar weight for stairs, ladders, railings and pipe. Thus, 75T is subdivided into equal parts of 25T each for the outfitting forward, mid and aft respectively. The anchor and chain weight is estimated on the basis of design rules by the International Association of Classification Societies, IACS (IACS, 2014). A weight of 30T attributed to the weight of the anchor and chain is thus added to outfitting forward, making a total of 55T for ferrous scrap (W01) originating from element U06: outfit for.

The material stream non-ferrous scrap (W02) generated from the outfitting elements is estimated to be a total of 6T based on the following discussion. Within the outfitting part (elements U06 to U08), non-ferrous material such as copper and brass are mainly used for sidelights, handrails, sounding pipe caps, fire main valves, sprinkler system and heads of vent and overflow pipes on weather deck (CDA, 2015) while aluminium and its alloys are fitted in navigation spaces because of their non-magnetic characteristics (Barrass, 2004). Weight of such outfitting is estimated to be very small amount at about 2T each for outfitting forward (U06), mid (U07) and aft (U08). Further data is needed to verify these estimates.

The material stream machinery (W03) generated from the outfitting elements consist of the windlasses, mooring winches and steering gear (Bertram and Schneekluth, 1998, Papanikolaou, 2014). Generally, there is no machinery located at the midship which means material stream machinery (W03) does not originate from the element U07: outfit mid. The total weight of all the equipment aft and forward is estimated at 60T and 30T respectively by author's experience and industry experts' opinion.

In order to quantify remaining five material streams W04, W05, W06, W08, W09 originating from elements U06, U07, U08 it is assumed that the percentages estimated by DNV study (Andersen et al., 2001) holds true for the material streams minerals (W05) and plastics (W06) because DNV study focussed on sampling of materials of environmental concerns such as asbestos and glass wool in minerals category and PVC in plastics category (Andersen et al., 1999). The quantification of material streams W04, W08 and W09 is carried out by dividing the remaining non-estimated weight of outfitting elements proportionally. The proportion numbers for material streams are used from the DNV study (Andersen et al., 2001) because they are the best available estimates in the literature.

Table 4.5: Distribution of weight elements of the case ship into material streams

S. no.	Stability manual element	W01: Fe	W02: Non-Fe	W03: M/C	W04: E&E	W05: Minerals	W06: Plastics	W08: Joinery	W09: Misc.	Total (Tonnes)
1	M01: Machinery piping	90.0	5.0							95.0
2	M02: Electrical		12.5		12.5					25.0
3	M03: Bridge equipment				6.0					6.0
4	M04: Tools and Spares	15.0								15.0
5	M05: Main Engine			220.0						220.0
6	M06: Shafts	28.0								28.0
7	M07: Propeller		17.0							17.0
8	M08: Auxiliary engines			38.0						38.0
9	M09: Machinery comp	75.0				5.0				80.0
10	M10: Machinery equip			114.0					1.0	115.0
11	U01 - U04: Crane 1-4			228.0						228.0
12	U05: Hatches	880.0								880.0
13	U06: Outfit For	55.0	2.0	30.0	13.6	66.0	31.7	16.3	5.4	220.0
14	U07: Outfit Mid	25.0	2.0		32.4	60.0	28.8	38.8	12.9	200.0
15	U08: Outfit Aft	25.0	2.0	60.0	73.4	150.1	72.0	88.1	29.4	500.0
16	U09: Paint and Cathodes		76.0						54.0	130.0
17	S01 – S16: Steel hull elements	8451.0								8451.0
18	X01: Tol and Marg	-203.9								-203.9
	Total:	9440.1	116.5	690.0	137.9	281.1	132.5	143.2	102.7	11044.1
	Percentage:	85.48	1.05	6.25	1.25	2.55	1.20	1.30	0.93	100.00

In this methodology, liquids such as lube oil and fresh water contained within various machines are not quantified separately. They are considered as a part of machinery weight. The final distribution of the weight elements of the case ship into various material streams is compiled in Table 4.5 and its material composition as calculated using the proposed methodology is shown by Figure 4.1.

The material composition shown in Figure 4.1 is based on the lightweight distribution of the case ship as recorded in its stability manual. However, final material composition may differ from this because of the fact that the weight of an EOL ship is usually more than its LDT due to the unaccounted weight added during its lifetime. This extra weight includes operationally generated waste, stores, spares, paint on ship structure and remaining quantity of liquids such as fuel oil, lube oil, sludge, sewage etc. Generally, ship's LDT is updated by classification society in case of major structural modification or machinery retrofitting. In most cases, material stream liquids, chemicals, and gases (W07) would be added to the final material composition. The quantity of this material stream depends on the remaining on board (ROB) figures recorded when an EOL ship reaches the recycling yard.

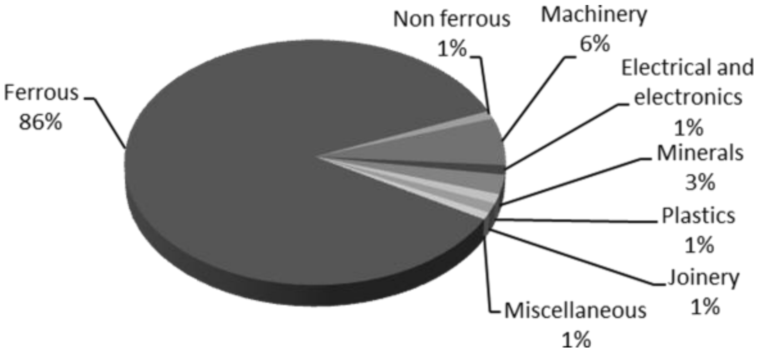


Figure 4.1: Material composition of the 11000 LDT handymax bulk carrier based on its stability manual

4.5 Analysis and recommendation

A methodology for the material quantification of an EOL ship using its stability manual is presented in this chapter. This methodology is unique in nature because it uses the information that is readily available to a ship recycling yard. It can not only be used by ship recycling yards to quantify the material streams of an EOL ship with a greater degree of accuracy but also be applied for further research in this field. The accurately quantified material streams can help recycling yards planning the recycling process and perhaps in a later stage the equipment utilisation can also be improved, further reducing the costs of the yard. Furthermore, the uncertainty in calculating the offer price can be reduced.

A drawback of this methodology is that it relies heavily on the level of detail of the lightweight distribution recorded in the ship's stability manual. Since the number of weight elements of the lightweight distribution is not standardized by any international rule, their level of detail can differ from ship to ship. In this chapter, it is recommended that there should be a standardized format of the weight elements of the lightweight distribution of the ship. The number of weight elements should be comprehensive enough to reveal the material composition of the ship.

The developed methodology is able to predict up to 88 percent (9679 tonnes) of the material quantity of the case ship without any ambiguity. The approximation is done only for the 12 percent of LDT (1365 tonnes) owing to the missing information regarding the individual components forming elements M01, M02, M09, M10, and U06 to U09 of the lightweight distribution (Figure 4.2). The information required for more accurate material quantification include the breakdown of M01 into weight of ferrous and non-ferrous piping, M02 into weight of cables and electrical equipment, M09 into the weight of individual components such as heat and noise insulation, and ferrous material stream formed by railings, stairs, floor gratings, floor plates etc., M10 into the weight of individual equipment such as level switches, thermometers and batteries, U06 to U08 into the weight of individual components and U09 into the weight of paint and cathodes separately. The outfitting elements form the highest percentage (67%) of weight of the components with missing information.

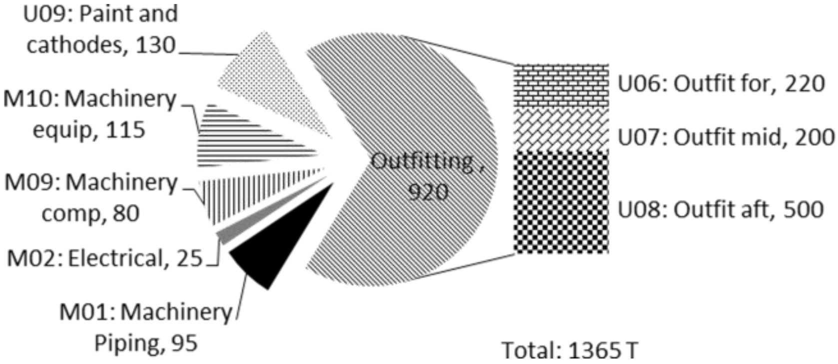


Figure 4.2: Weight (T) of elements with missing information

Most of the information which is required to estimate the ship’s material composition to a greater degree of accuracy is available when the ship is constructed, yet it is not passed on to the ship recycling yard at the end of ship’s economic life. It is thus recommended that the detailed work breakdown structure (WBS) having weights and centres calculation used during ship design and construction must be preserved and kept on board. It must be transferred from the shipyard to the recycling yard through the ship owners over the lifetime of a ship for further enhancement of the accuracy of the developed methodology. The availability of detailed WBS and stability manuals of EOL ships would also enhance the prospects of data collection related to material composition of EOL ships improving the current scenario where researchers face hurdles in collecting such data. The sharing of such information with all the stakeholders can go a long way in developing the ship recycling industry into safe and environmentally friendly industry.

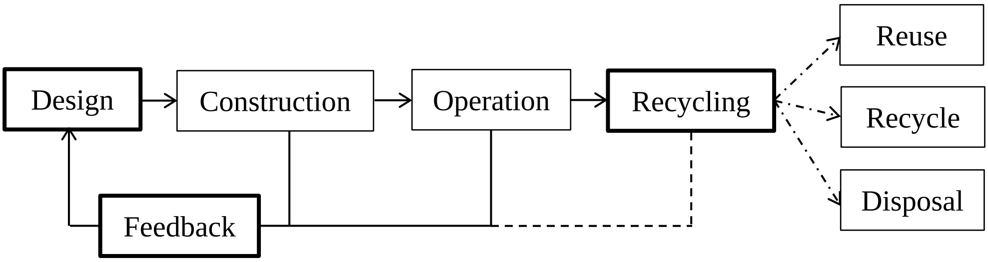


Figure 4.3: Feedback to design phase of the ship’s life cycle.

The aforementioned recommendations are feedback from the recycling phase to the design phase of a ship’s lifecycle. Such a feedback generated as a result of analysis of ship recycling process can improve ship designs to achieve safe and environmentally sound ship recycling (Jain et al., 2014) as depicted by Figure 4.3. The collaboration between design of products and waste management is investigated by Ordoñez and Rahe (2013) and Ardente et al. (2015) while van Schaik and Reuter (2004), Ferrão and Amaral (2006), Mayyas et al. (2012) and Tian and Chen (2014) investigated the design for dismantling (DfD) concept for EOL vehicles. The application of DfD concept on ships is studied by Alkaner et al. (2006), McKenna et al. (2012), Sivaprasad and Nandakumar (2013) and Jain et al. (2014). All of them have emphasized the importance of designing a ship in such a way that it is safe and environmentally friendly to recycle by establishing a link between the recycling phase and the design phase of the ship’s life cycle. This link in the form of feedback from the recycling phase to the design phase ensures that ship's recycling phase is analysed and improved and at the same time ship designs are also improved based on the feedback from the recycling phase to achieve safe and environmentally sound ship recycling.

4.6 Conclusion

In the absence of a scientific tool to quantify material streams of EOL ships, recycling yards resort to use expert opinion and their own judgement based on the experience to quantify material streams of an obsolete vessel they are working upon. This estimation is, to some extent, also the basis of the price offered to a ship owner and for the planning of processes on a recycling yard.

An extensive literature survey of the subject found no methodology that can be used to quantify the material streams of an individual ship. Upon investigation, it was determined that the stability manual of an EOL ship can be used to determine the material composition of the ship with a much more accuracy than determined using the present quantification methods.

Although, ship's stability manual does not contain all the information required for an accurate estimation of material streams; it was proved in this chapter, by quantifying material streams of a handymax bulk carrier with 88% accuracy, that stability manuals can be used to quantify material streams of EOL ships using the developed methodology. The lack of standardization for the number of weight elements of the lightweight distribution given in the stability manual is a pitfall for this methodology. It can be overcome by making it mandatory for ship building yards to provide a detailed breakdown of weight elements in the lightweight distribution of a ship. The estimation of weight elements at a fairly detailed level is anyway carried out by ship building yards in order to calculate costs and other ship stability parameters accurately. It is just the matter of reporting it in the ship's official documents such as stability manual.

The use of stability manual means developed methodology uses the information from the design stage of the ship's lifecycle. The missing link between the design stage and the recycling stage of the ship's lifecycle for an accurate quantification of material streams is the detailed WBS classification system used during the ship construction. The ship recycling yard can use ship's stability manual and detailed WBS classification system not only to determine ship's material composition but also to improve resource allocation and waste management. Moreover, storage capacity of the recycling yard and the activities of the ship recycling process can be planned using MFA based on the quantified material streams resulting in a cost effective, safe and environmentally sound ship recycling.

In this chapter, the proposed methodology is applied on an 11000 LDT handymax bulk carrier to estimate its material composition using the stability manual. It is a test case which proves that working with the ship building yards can further validate this methodology by applying it on different types of new build ships using their stability manuals and WBS information. This can result in a standardized format of the weight elements of the lightweight distribution of ships helping the recycling yards to accurately determine the material composition of every EOL ship they are working upon.

CHAPTER 5

MATERIAL FLOW ANALYSIS MODEL[**]

“Almost all new ideas have a certain aspect of foolishness when they are first produced.”

\- Alfred North Whitehead (1861-1947), Mathematician

[**] This chapter is published as

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2017. Material flow analysis (MFA) as a tool to improve ship recycling. *Ocean Engineering*,130, 674-683, http://dx.doi.org/10.1016/j.oceaneng.2016.11.036

Minor changes are made to facilitate integration in this thesis, e.g., ‘paper’/‘article’ is changed to ‘chapter’ and square brackets are used to add new text.

As discussed in Chapters 1 and 3, the green ship recycling has to reduce or even close the existing price gap between green and substandard ship recycling to promote environmentally friendly green ship recycling. They should therefore either increase the revenue or lower the cost of recycling a ship without compromising the HSE standards. The forthcoming international regulations on ship recycling such as the Hong Kong convention (HKC) and EU ship recycling regulation (EUSRR) must also be considered. The analysis carried out in Chapter 3 suggests that such problems could be tackled using Material Flow Analysis (MFA), a tool widely used by the environmental engineers.

This chapter investigates the applicability of MFA to the ship recycling industry to achieve the objectives of the green ship recycling yards. The methodology and input data for carrying out MFA on a ship recycling yard is explained. The MFA is implemented using a 2006 built, 11044 tonnes lightweight bulk carrier as a case study for assessing its applicability to the ship recycling industry. The application of MFA for various ship recycling planning related tasks is also discussed. These tasks include investigating the flows of economic and non-economic value streams on a yard, assessing and planning the ship recycling process, and anticipating various recycling scenarios. The chapter concludes by explaining the importance and shortcomings of applying MFA to the ship recycling industry.

5.1 Introduction

[As discussed in Chapter 2,] Ship owners scrap their ships for various reasons, such as ageing, technical obsolescence, low earnings, high scrap prices and bad market expectations (Stopford, 2009). Though the decision on when to scrap a ship depends on the complex dynamics of these factors, the decision on where to scrap a ship is fairly simple. Most ship owners base this decision primarily on the price offered by the ship recycling yard to buy an end-of-life (EOL) ship. The recycling yard offering the best price usually wins the contract. Additionally, the location of the ship recycling yard and its distance from the last port of the ship is also an important factor (Jain et al., 2016b). However, the sustainability related factors such as environmental footprint and the quality of the ship recycling process employed at the yard hardly influence the ship owners’ decision in selecting a ship recycling yard.

[In Chapter 2, it was also shown that] Most recycling yards are located in India, Bangladesh, Pakistan, China and Turkey. These countries are major ship recycling centers in terms of annual lightweight tonnage recycled. The ship recycling yards compliant with either the international standards for health, safety and environmental (HSE) management or the ship recycling regulations such as Hong Kong convention and EU ship recycling regulation are considered innocuous to environment, health and safety of the workers. Such yards are referred to as green recycling yards in this thesis. According to an estimate by Abdullah et al. (2013), the annual global capacity of green recycling was around 780,000 lightweight tonnes (LDT) in 2012. Such green yards generally offer a lower price compared to other yards operating in the same region. This price gap is mainly due to the extra cost of maintaining high HSE standards and investment in recycling facilities and workforce welfare required for green ship recycling (Dev, 2010). The cost of the total process must be lower than the income for a recycling yard to be profitable. Therefore, the green ship recycling yards are unable to match the price offered by other non-green yards employing primitive recycling techniques. In essence, the green ship recycling is mainly driven by the regulations and economics.

[As discussed in Chapter 1,] The green ship recycling yards are economically unattractive to most ship owners due to the generally lower offered price for the same ship. These yards must reduce or even close the existing price gap between green and non-green ship recycling to promote environmentally friendly green ship recycling. They must either increase the revenue or lower the cost of recycling a ship. The price gap must be reduced without compromising the HSE standards and considering the forthcoming international regulations on ship recycling such as the Hong Kong convention and EU ship recycling regulation. One way for green recycling yards to achieve this objective is to adopt certain scientific tools and techniques used in other similar but matured industries such as automobile recycling and aircraft recycling. However, Jain et al. (2016b) determined that the differences due to large size, various types, large age range, infrequent supply and dynamic composition of ships makes it difficult to use the tools implemented in other recycling industries.

Production and manufacturing firms reduce costs and increase profit margins by analyzing and optimizing their processes using the principles of operations management. Alkaner et al. (2006) showed that ship recycling can be considered as a production system that supports the recovery, processing and resale of materials and components at the end of ship’s useful life. Therefore, tools and techniques used within the various production systems should be analysed for their applicability to the ship recycling industry. Although such operations management tools might be capable of reducing the costs of green ship recycling, they must be supplemented with the analytical tools used in environmental engineering to overcome the unique challenges faced by green ship recycling industry in terms of environment related issues. For example, end-of-life ships contain all sorts of hazardous materials which must be treated suitably to avoid harming the environment, health and safety of the workers. The complexity of ships in terms of structural arrangement and use of various types of materials is also a challenging factor.

In recent times, the focus of policy makers, governments and intergovernmental organizations has been shifted to the anthropogenic environmental problems such as increasing global pollution, depleting natural resources, climate change, etc. The need to carry out scientific analysis to develop and implement stricter rules and regulations to tackle such problems has led to the development of innovative scientific tools and techniques in the field of environmental engineering. Material flow analysis (MFA) is one such tool that is widely used by the environmental engineers. Its applicability to the ship recycling industry must be investigated to achieve the objectives of the green ship recycling yards.

5.2 Methods and data

In this chapter, inspiration from both operations management and environmental engineering is gathered to implement a well-known technique to improve the ship recycling industry. Therefore, analytical tools of both domains are reviewed. The challenges faced by green ship recycling industry and the inability of various operations management tools to address those challenges are discussed. This chapter concludes that MFA, an analytical tool used in environmental engineering, is the most practical tool of those reviewed. The methodology and input data for carrying out MFA on a ship recycling yard is explained. The key takeaways of this research are also summarized.

5.2.1 Operations management

Operations management is the systematic planning, execution and control of operations (Slack et al., 2010). ‘Operations’ is an umbrella term that includes services and manufacturing. Operations management involves scheduling work, assigning resources, managing inventories, assuring quality standards and process-type decisions such as capacity decisions, maintenance policies, equipment selection, worker-training options and the sequence for making individual items in a product-mix set (Gupta and Starr, 2014).

In the last few decades, due to significantly increased levels of competitiveness in modern industry, a range of methodologies and techniques aimed at improving the performance, productivity and profitability of the operational activity have been developed (Grünberg, 2003, Hernandez-Matias et al., 2008, Hernandez-Matias et al., 2006, Shah and Ward, 2003). These techniques can be broadly classified into two main categories: diagnostic tools (process mapping, process flowcharting, value stream mapping, pareto analysis, fishbone diagrams, etc.) and improvement tools (just-in-time(JIT), total quality management (TQM), total preventive maintenance (TPM), theory of constraints (TOC), business process reengineering (BPR), etc.). A wide variety of such management practices, methods, tools and techniques are encompassed under a production approach called lean manufacturing (Womack and Jones, 2010, Womack et al., 1990), based on the Toyota Production System (Ohno, 1988).

All manufacturing and production systems involve the transformation of inputs (labor, machines, and materials) into desired goods and services. The inputs are combined by the process, often including many sub-processes, resulting in the production of units of goods or the creation of types of services. Ship recycling is a one-of-a-kind production system where the inputs are the ship, labor and equipment (such as cranes, gas torches, fork lifts, etc.) which are transformed into outputs (such as ferrous scrap, non-ferrous scrap, re-usable items, waste, etc.) as a result of various processes, such as pre-cutting, cutting and post-cutting.

Lean thinking has been successfully applied to the industries where inputs are transformed into outputs. This includes the manufacturing (Detty and Yingling, 2000, Shah and Ward, 2003, Taj, 2008, Yang et al., 2011), healthcare (Brandao de Souza, 2009, Jones and Mitchell, 2006, Mazzocato et al., 2010, Waring and Bishop, 2010), construction (Ballard and Howell, 1994, Koranda et al., 2012, Salem et al., 2006, Thomas et al., 2003) and process industry (Melton, 2005, Abdulmalek and Rajgopal, 2007, King, 2009). However, it must still be investigated whether lean and other aforementioned tools can be implemented to improve the competitiveness of green ship recycling.

5.2.1.1 Lean manufacturing tools

The basis of lean manufacturing is to identify, measure and eliminate ‘waste’ from the system (Pavnaskar et al., 2003) to improve its performance. ‘Waste’, in the context of lean thinking, means any activity in a process that does not add value to the final product (Melton, 2005). The most sought after areas of improvement using lean tools are inventory and quality management because both these areas significantly drive down the costs in a normal production system. However, their application to the ship recycling industry is not feasible because (1) the high fluctuation in demand and supply on both the input and the output side of the ship recycling process (due to the cyclical nature of the shipping markets) can only be offset by creating buffers (inventory) in the ship recycling system, and (2) the quality of finished product of ship recycling i.e. scrap does not depend much on the ship recycling process. Instead, it depends on the construction, operation and maintenance of the ship.

5.2.1.2 Diagnostic tools

The diagnostic tools such as process mapping can be helpful in understanding the generic ship recycling process and identifying the problem areas that can be targeted not only to develop and make green ship recycling competitive but also to improve the ship recycling industry on the whole. In any industrial process there are three types of flows i.e. information, product and resources (Veeke et al., 2008). The information flow contains the technical data controlling the operation itself. The product flow is initiated due to the transformation of raw materials into delivered products as a result of the industrial process. The flow of resources includes the people and means required to make the product. Resources must enter the system and leave the system as ‘used’ resources. From a ship recycling yard’s point of view, the product flow (i.e. the flow of materials) is the most critical flow because it influences the revenue generation and the cost factors of a ship recycling project. These cost factors include the amount of resources (labor, cranes, forklifts etc.) required to dismantle a ship, the amount of waste and its management strategy. Therefore, a process mapping tool that focuses on material flow is ideal for analyzing and improving the ship recycling process.

5.2.1.3 Improvement tools

The application of improvement tools can also be beneficial for the ship recycling industry. For example, a tool to improve the efficiency of people, equipment, space and energy can result in reduced costs and larger profits (Meyers and Stephens, 2005). Such tools can help re-engineer the ship recycling process to utilize the resources (such as labor, cranes, equipment, etc.) further up the economic hierarchy of materials to extract as much value from the end-of-life ship as possible. However, in the case of green ship recycling, a yard must also employ resources to handle the materials which are lower down the economic hierarchy (such as hazardous materials) because it is important that the environment and the workers' health and safety are not compromised.

In conclusion, operations management tools offer a limited application within the green ship recycling industry due to its unique challenges discussed in above paragraphs. Therefore, it is worthwhile to review the tools used in environmental engineering to select an appropriate analytical tool. The environmental engineering tools might be more suitable to the ship recycling industry because this industry handles end-of-life products having hazardous materials. These materials need proper treatment and disposal to protect human health and environment at a competitive cost.

5.2.2 Environmental engineering

Environmental engineering is the study concerning the management of natural resources and the reduction of pollution and contamination of the environment caused by anthropogenic activities (Fränzle et al., 2012). Environmental studies require a thorough understanding of the material flows within and between the environment and the anthroposphere. For this purpose, a tool based on mass balance principle and system analysis called as material flow analysis (MFA) has been developed (Brunner and Rechberger, 2004).

MFA is an analytical method of systematic assessment of flows of materials within a complex system defined in space and time (Brunner and Rechberger, 2004). MFA is applied in diverse fields such as environmental management, industrial ecology, resource management and waste management. An MFA can also contribute to the design of better products that can be easily recycled once they become obsolete and turn into 'waste' (Brunner and Rechberger, 2004). It is anticipated that MFA can potentially be used by production, manufacturing and commercial entities as a standard analytical tool in decisions on materials management (Allen et al., 2009, Gould and Colwill, 2015, Brunner and Rechberger, 2004) to locate and examine inputs, outputs and source of waste materials. The materials and waste management is important to improve the competitiveness of a green ship recycling yard because it influences both cost and revenue of recycling an EOL ship. Therefore, MFA can be a suitable tool to analyze and subsequently improve the ship recycling process.

Before applying MFA, its applicability to a green ship recycling yard must be evaluated. Two aspects must be considered before applying MFA to a ship recycling yard. (1) From systems perspective, an analysis of a ship recycling yard is a micro-level analysis; nation or economy wide analysis being the macro-level while local (city, river-basin) analysis being the meso-level analysis (OECD, 2008) (2) From environmental management perspective, a ship recycling yard is essentially a waste management system managing EOL ships. Since an MFA is applicable for waste management on any system defined in space and time, from as small as a single treatment process plant to as large as a nation (Tang and Brunner, 2013), it can be applied on a ship recycling yard. Moreover, the applicability of MFA in waste management as a decision support tool (Brunner et al., 2004, Tang and Brunner, 2013, Arena and Di Gregorio, 2014, Stanisavljevic and Brunner, 2014) as well as a micro-level system flow mapping tool (Achinas, 2014, Bugallo et al., 2012, Kurdve et al., 2015, Rodríguez et al., 2011, Rybicka et al., 2015) is very well documented.

An MFA can be carried out using the software STAN (Cencic and Rechberger, 2008) not only to produce a graphical representation of a waste management system but also to determine the types of materials that flow into, within and out of the system. This can help manage the waste in such a way that the recycling process is not threatening to human health and environment, assists resource conservation and allows segregation of non-recyclables from recyclables so that an appropriate disposal strategy (landfill or energy recovery) can be implemented.

In this chapter; waste, from a ship recycling yard’s perspective is defined as any substance, material or object originating from dismantling an EOL ship and is required to be discarded and disposed appropriately in accordance with applicable laws, regulations, management standards and market conditions. An MFA applied to a ship recycling yard on a ship-by-ship basis can help determine the flows of materials through each stage of the recycling process. A known material flow for each ship can help a recycling yard determine the required number and capacity of resources (such as cranes, fork lifts, etc.) for each step of the recycling process, earning potential of each material stream, and the scale of waste generation during the recycling process. Such parameters can assist in developing a detailed plan of recycling a ship not only to reduce costs by increasing the efficiency of resources but also to implement better waste management strategies resulting in the implementation of ship recycling practices unthreatening to human health and environment.

In fact, waste management strategies such as ‘waste to energy’ can even result in an extra revenue stream for recycling yards willing to invest in advanced technologies that are suitable to handle the heterogeneous waste generated by recycling of ships. For example, the plasma gasification technology can convert waste into useful products such as vitrified glass, reusable metal and synthetic gas, which can be used to produce energy through generators, gas turbines and boilers (Pourali, 2010). The results of an MFA study can help determine the technical and economic feasibility of such capital intensive, advanced waste management technologies.

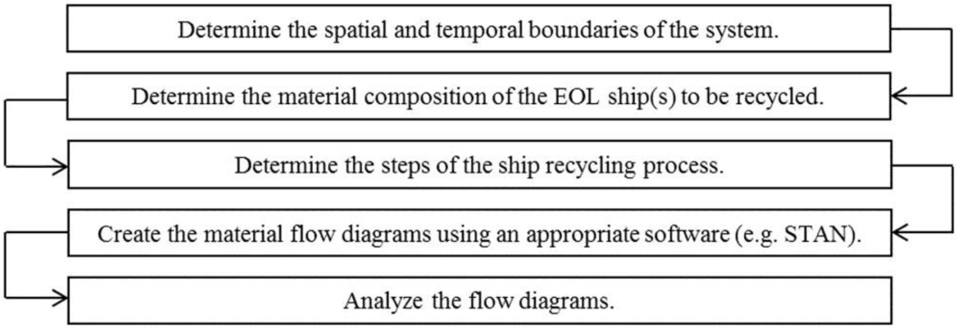


Figure 5.1: Step by step methodology for MFA on a ship recycling yard

There are clear advantages of using MFA as an analysis tool on a ship recycling yard but the quality of results depend on the quality of the input data. Data collection has historically been a problem in the ship recycling industry because of skepticism among recycling yards and a lack of co-ordination among the various stakeholders. Moreover, since research in this area of study is still in its preliminary stage, few databases collecting the requisite data exist. Various authors (Demaria, 2010, Sarraf, 2010, Sujauddin et al., 2015) have discussed this issue of unavailability of data hampering the research in ship recycling field. In the next section, a methodology to collect data and carry out MFA on a ship recycling yard is discussed.

5.2.3 Methodology and input data for MFA on a ship recycling yard

For carrying out an MFA on a ship recycling yard, the steps shown in Figure 5.1 can be followed. First, the space and time boundaries of the system must be defined. Secondly, material composition of EOL ship(s) to be recycled must be determined. Thirdly, various steps of the ship recycling process must be established. Finally, flow diagrams can be created using the open source software ‘STAN’. The flow diagrams can be analyzed to meet the requisite objective.

5.2.3.1 Spatial and temporal boundary

The spatial boundary of an MFA for ship recycling can range from all world-wide ship recycling yards to a single ship recycling yard. The temporal boundary can range from a few years to a single day. The choice of spatial and temporal boundaries depends on the objective of the MFA. In this chapter, since the objective of MFA is to make green ship recycling yards competitive with other yards, a particular green recycling yard can carry out an MFA on each ship it will recycle to determine the areas of improvement within the recycling process. Therefore, the spatial boundary is the recycling yard itself while the temporal boundary is the time required to complete one recycling project (e.g. 3 months for a bulk carrier).

5.2.3.2 Quantification of material composition of a ship

The study carried out by Jain et al. (2016b) determined that out of the nine studies (Adak, 2013, Andersen et al., 2001, Andersen et al., 1999, Demaria, 2010, Hess et al., 2001, Hiremath et al., 2015, Sarraf, 2010, Sujauddin et al., 2015) available on the quantification of material composition of EOL ships, none present a methodology that can be used by the ship recycling yards to determine the material composition of an individual ship. Therefore, they presented a methodology which determines the material composition of a 2006 built, 11044 tonnes lightweight handymax bulk carrier on the basis of its lightweight distribution provided in its stability manual. For this research, this particular ship is used as a case ship. The material composition of the case ship calculated by Jain et al. (2016b) does not contain the values for the material stream ‘liquids, chemicals and gases’ (LCG) because they considered that the most of the LCG material stream is operationally generated and is not part of the ship’s lightweight. The material composition of the case ship corrected for LCG material stream is compiled in Table 5.1. The value for LCG material stream is taken from a study carried out by Andersen et al. (2001) for a bulk carrier.

5.2.3.3 Steps of the ship recycling process

The third step to carry out an MFA on a ship recycling yard is to determine the steps of the ship recycling process. Though ships are recycled by employing different docking methods (i.e. beaching, slipway, alongside and dry dock) in different parts of the world, the process of dismantling and recycling a ship takes place in a series of steps which are independent of the method employed to dock the vessel. Ship recycling is generally performed by cutting away large sections of the ship’s hull, which are then moved to shore for further dismantling. The entire recycling process can be divided into three main phases – pre-cutting, cutting and post-cutting (DEFRA, 2007, OSHA, 2010, Sivaprasad, 2010, USEPA, 2000). Each phase of the ship recycling process is a process in itself because some form of transformation takes place. The pre-cutting process involves various surveys and hull preparations for gas cutting. The cutting process is the process where actual cutting of steel hull and machinery into small pieces takes place. The post-cutting process involves sorting and segregation of materials. Each of these processes can be examined further to determine other processes that take place within them.

Table 5.1: Material composition of an 11044 T lightweight handymax bulk carrier based on Andersen et al. (2001) and Jain et al. (2016b)

S.no.	Material Streams	Quantity (% of LDT)
1.	Ferrous scrap	84.60
2.	Non-ferrous scrap	1.04
3.	Machinery	6.18
4.	Electrical and electronic waste	1.24
5.	Minerals	2.52
6.	Plastics	1.19
7.	Liquids, chemicals and gases	1.03
8.	Joinery	1.28
9.	Miscellaneous	0.92

5.2.3.4 Material flow diagrams

In order to develop the material flow diagrams using STAN, data for the input and output flow of each process must be fed by the user as far as practicable. In case the input or output flow is not known, user can feed the transfer coefficients of the processes. A transfer co-efficient of a process defines the relationship between the input and output flows of a process. For example, an input flow to a process can be divided into two or more output flows based on the defined ratios. Such data can be generated by reconciling the material composition data of the ship. Based on such data, STAN calculates the value of each flow. If the user defined data is not sufficient to perform such calculation, STAN displays an error message. The flows of materials of an EOL case ship on a recycling yard are presented in the next section.

5.2.3.5 Assumptions

The aim of carrying out an MFA for the case ship is to understand the costs and revenues associated with its recycling. Thus, all material streams originating from each process are categorized into two major streams, economic value stream (EVS) and non-economic value stream (NEVS). Economic value stream is the stream having the products which can either be sold for reuse or recycling, resulting in cash in-flow for the recycling yard. Non-economic value stream is the stream having the products which needs to be disposed of either at a waste treatment facility or at landfill sites resulting in cash out-flow for the recycling yard. The distribution of material streams into the EVS and NEVS can differ from one recycling yard to another depending on the factors such as location, recycling practices, second hand market, regulations, etc. Since this chapter does not focus on a specific recycling yard and due to the limitations in finding accurate data for the material composition of the case ship and for the input and output flows of the processes, it is necessary to make certain assumptions on the same in order to explain how MFA can be used within the context of ship recycling.

The assumptions made here represent a scenario where there is an existing scrap market for ferrous and non-ferrous scrap, and a second-hand market for items such as electrical and electronic waste, joinery, liquids (waste oil, sludge, fuel oil, lube oil, etc.) and machinery. For example, in Apr-2016 electrical cables (Rs. 100-150 per kg), electric motors (Rs. 70-80 per kg), glass wool insulation sheets (Rs. 2-4 per kg), sludge (Rs. 1-2 per kg), waste oil (Rs. 600-1100 per barrel), scrap machinery (Rs. 65-80 per kg), etc. were being legally sold in the second hand market at Alang, India at the prices mentioned in the brackets (Agarwal, 2016b).

Therefore, for the purpose of this research, the following assumptions on economic and non-economic value streams have been made. Ferrous scrap, non-ferrous scrap, machinery, electrical and electronic waste are considered a part of the EVS while plastics and miscellaneous material streams are considered a part of the NEVS. Both, minerals and joinery are divided equally into the EVS and NEVS. The NEVS part of minerals represents asbestos while the EVS part represents reusable insulation. Out of the 1.03% of material stream LCG, 1% is assumed to be liquids while the remaining is assumed to be chemicals and gases. Liquids are divided equally into the EVS and NEVS while chemicals and gases are considered part of the NEVS. The EVS part of liquids represent waste oil, sludge, fuel oil, lube oil, etc. while the NEVS part of liquids represent sewage, bilge water, etc. The assumptions related to the division of material streams into EVS and NEVS are shown in Table 5.2.

Table 5.2: Assumptions related to the division of material streams of the case ship into EVS and NEVS

S.no.	Material Streams	EVS	NEVS	Remarks
1.	Ferrous scrap	100%	-	Output of ‘cutting’ sub-process.
2.	Non-ferrous scrap	100%	-	Output of ‘cutting’ sub-process.
3.	Machinery	100%	-	Output of ‘cutting’ sub-process. 50% machinery is assumed reusable and 50% as scrap machinery.
4.	Electrical and electronic waste	100%		Output of ‘pre-cutting’ sub-process.
5.	Minerals	50%	50%	Output of ‘pre-cutting’ sub-process.
6.	Plastics	-	100%	Output of ‘pre-cutting’ sub-process.
7.	Liquids, chemicals and gases (Liquids (L), Chemicals and gases (CG))	50% L	50% L, 100% CG	Output of ‘pre-cutting’ sub-process.
8.	Joinery	50%	50%	EVS is output of ‘pre-cutting’ sub-process and NEVS is output of ‘cutting’ sub-process.
9.	Miscellaneous	-	100%	Output of ‘cutting’ sub-process.

5.3 Results

The most basic level of the flow diagram for recycling of the case ship (based on the assumptions mentioned in Table 5.2), developed by software STAN, is shown by Figure 5.2. This figure combines the three main processes: pre-cutting, cutting and post-cutting. The next level of the flow diagrams providing the details of the sub-processes of pre-cutting, cutting and post-cutting are shown in Figure 5.3, Figure 5.4 and Figure 5.5 respectively. These diagrams provide more insight into the basic level of the ship recycling process (Figure 5.2) by showing the quantities of materials flowing into and out of each sub-process, in terms of percentage of LDT. The red coloured flows represent the user defined data while the flows in black represent the data calculated by STAN. The boxes outlined in blue represent a process having sub-processes. Material flows in these diagrams depict the maximum obtainable amount of each material calculated with respect to the assumptions made for this research.

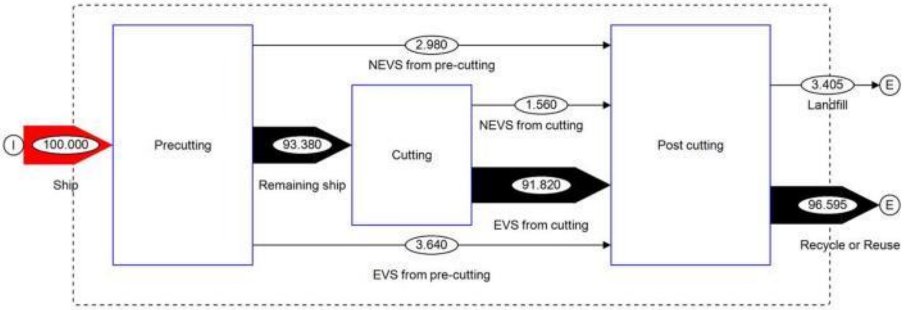


Figure 5.2: Ship recycling process of the case ship showing the quantities of material flow in terms of percentage of LDT

5.3.1 Pre-cutting

The pre-cutting process comprise of all the activities of the ship recycling process that take place before the cutting of an EOL ship starts. It consists of various sub-processes such as the removal of loose items; removal of liquids; removal of hazardous materials; removal of insulation, flooring and tiling; and removal of cables and electrical equipment. The economic value stream and non-economic value stream originating from pre-cutting is an input for post-cutting where further separation and sorting takes place. It is assumed that the economic value stream of pre-cutting process is comprised of loose items (such as furniture, lifesaving appliances, firefighting appliances, galley appliances, household appliances, spare parts, paint drums, etc.) having second hand value; liquids (such as waste oil, lube oil, fuel oil, etc.); non-hazardous re-usable insulation (glass wool) and copper cables. The non-economic value stream is assumed to comprise of hazardous materials such as asbestos, PCB, ozone depleting substances, etc.; ballast water; sewage and other waste that needs to be disposed of safely. Based on these assumptions, the assumptions made in Table 5.2 and the values of material streams (Table 5.1), it is estimated by MFA that 2.98% and 3.64% of LDT of the case ship would originate as NEVS and EVS respectively from the pre-cutting process. The remaining ship (93.38% of LDT) would flow into the next process, cutting.

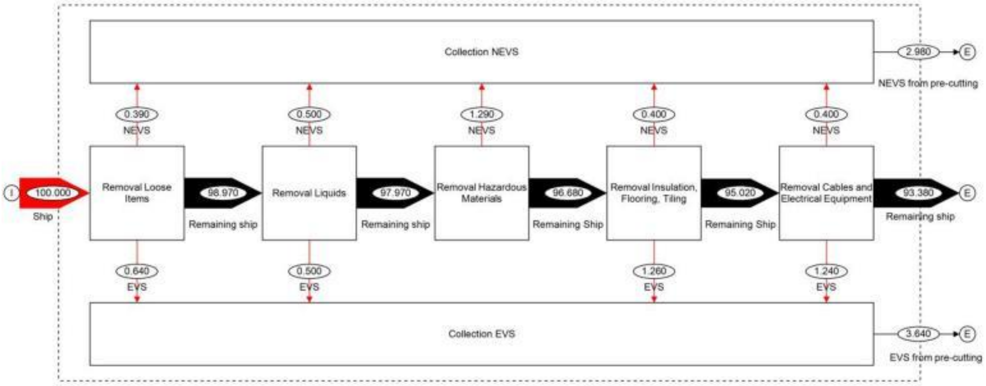


Figure 5.3: Pre-cutting process of the case ship showing the quantities of material flow in terms of percentage of LDT

5.3.2 Cutting

The cutting process is divided into ‘primary cutting’ and ‘secondary cutting’ sub-processes. The ‘primary cutting’ is the process where a ship’s hull is cut into ferrous blocks and non-ferrous items are extracted. The ship’s machinery is cut from the base either to be sold in the second-hand market as reusable machinery or to be fed into the ‘secondary cutting’ sub-process as scrap machinery. The segregation of machinery into reusable and scrap machinery is depicted by the sub-process ‘machinery segregation’. The machinery is turned into scrap if it is not saleable in the second-hand market.

Both ‘primary cutting’ and ‘secondary cutting’ sub-processes are connected by a ‘segregation of ferrous, non-ferrous and machinery’ sub-process, which depicts the segregation of ferrous blocks, non-ferrous items and machinery. It also depict the transfer of bigger blocks from the primary cutting area to the secondary cutting area. The ferrous blocks and obsolete machinery having no second-hand value (scrap machinery) act as an input to the ‘secondary cutting’. Non-ferrous items, owing to their small size, do not need to be fed into the sub-process ‘secondary cutting’. The ‘secondary cutting’ is the process where ferrous blocks are cut into steel plates and smaller pieces of steel scrap while the scrap machinery is cut into the smaller pieces of machinery scrap.

The processes of ‘primary cutting’ and ‘secondary cutting’ are executed mainly using gas cutting torches. The cutting process results mainly in an economic value stream owing to the high value of ferrous and non-ferrous scrap. The only non-economic value stream out of the cutting process is paint chips and other waste which can neither be sold in the second hand market nor can be recycled as scrap. Based on the values of material streams (Table 5.1) and the assumptions made in the beginning of this section (Table 5.2), it is estimated by the MFA that 1.56% and 91.82% of LDT of the case ship would originate as NEVS and EVS respectively from the cutting process. Both these streams, along with NEVS and EVS from the pre-cutting process, are fed into the post-cutting process.

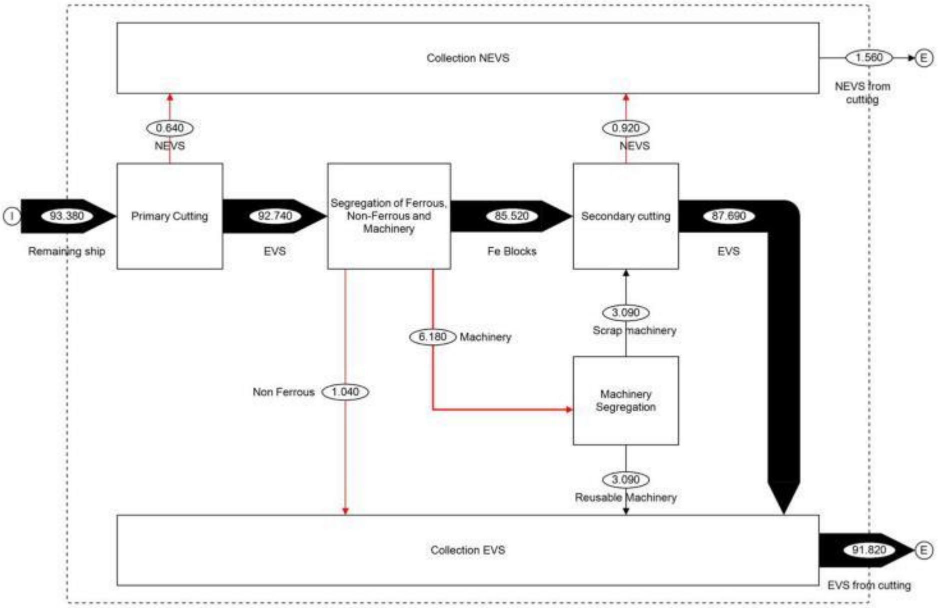


Figure 5.4: Cutting process of the case ship showing the quantities of material flow in terms of percentage of LDT

5.3.3 Post-cutting

The post-cutting process comprise of ‘pick-up and storage’, ‘separation’ and ‘segregation & transport’ sub-processes. First sub-process of post-cutting is ‘pick-up and storage’ where the EVS and NEVS are picked-up from their respective originating sources for storage. Eventually EVS is fed to the sub-process ‘segregation and transport’, where products are sent either for reuse or recycling. The NEVS originating from sub-process ‘pick-up and storage’ is fed into sub-process ‘separation’ where products are further separated into NEVS and EVS. The sub-process ‘separation’ is an important activity of the post-cutting process where further separation of products which were originally considered as non-economic value owing to their large amount of waste takes place. For example, a machinery component, such as a valve or pipeline insulated with asbestos, may be initially considered as NEVS. However, it can be further separated into metal (EVS) and asbestos insulation (NEVS) if the cost of separation (asbestos removal) can be offset by the metal value. The NEVS and EVS originating from the sub-process ‘separation’ is fed into the sub-process ‘segregation and transport’ where the EVS is transported either for reuse or recycling and the NEVS is transported either to landfill sites or to downstream disposal sites. All downstream activities (including reuse, recycling, disposal, landfill, etc.) are considered out of the system boundary of the ship recycling process because these activities do not take place on the ship recycling yard.

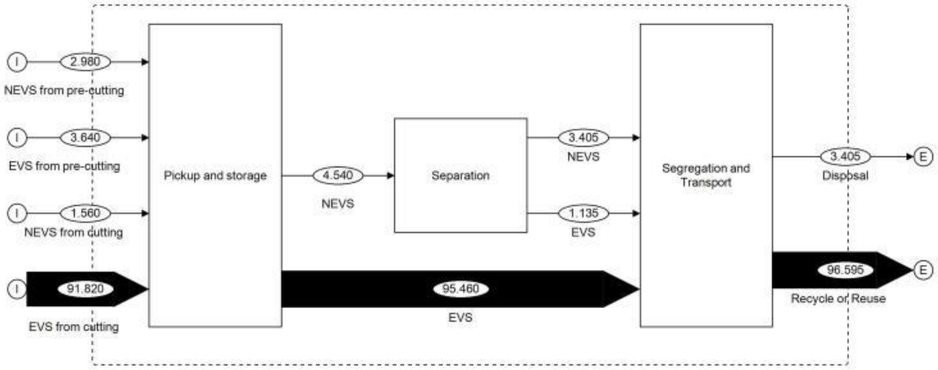


Figure 5.5: Post-cutting process of the case ship showing the quantities of material flow in terms of percentage of LDT

Based on the assumptions made in the beginning of this section (Table 5.2) and the values of material streams (Table 5.1), it is estimated by means of an MFA that 3.40% of LDT of the case ship would be sent for disposal (in most cases to a landfill site) and 96.60% of LDT of the case ship can either be reused or recycled. This effectively means that recycling an 11044 LDT handymax bulk carrier would result in 375 T (3.40%) of waste needing either landfill or other disposal techniques while the remaining amount 10669 T (96.60%) can either be recycled or reused by selling in the scrap market, if the assumptions made in this research are found true. These figures also assume that about 25% of the weight of the NEVS can be extracted as EVS during the ‘separation’ sub-process of the post-cutting process. This value can change depending on the separation capacity and techniques employed by the recycling yard.

The amount of EVS and NEVS obtained from each sub-process of recycling the case ship as derived from the MFA diagrams for the applied assumptions is shown in Table 5.3.

Table 5.3: The quantities of economic and non-economic value streams obtained from each sub-process of recycling the case ship under the applied assumptions

S.no.	Process	Sub-process	EVS		NEVS	
			Percentage of LDT	Tonnes (rounded up)	Percentage of LDT	Tonnes (rounded up)
1.	Pre-cutting	Removal loose items	0.64	71	0.39	43
2.		Removal liquids	0.50	55	0.50	55
3.		Removal hazardous materials	0.00	0	1.29	142
4.		Removal insulation, flooring, tiling	1.26	139	0.40	44
5.		Removal cables and electrical equipment	1.24	137	0.40	44
6.	Cutting	Primary cutting	92.74	10242	0.64	71
7.		Secondary cutting	87.69	9685	0.92	102
8.	Post-cutting	Pick-up and storage	95.46	10542	4.54	501
9.		Separation	1.14	126	3.40	375
10.		Segregation and transport	96.60	10669	3.40	375

5.4 Discussion

5.4.1 Data accuracy

The results of the MFA depend on the accuracy of input data and understanding of various sub-processes of the ship recycling process. It is not possible to conduct an MFA study on a ship recycling yard without knowing the material composition data of ships and the relation between the input and output flows of each sub-process of the ship recycling process. The material flow analysis carried out in the previous section determined the quantity of waste and recyclables generated as a result of dismantling an EOL handymax bulk carrier under the applied assumptions.

The MFA shown in this chapter is only for one ship under certain assumptions. However, ship recycling yards recycle several ships at the same time in most cases. Therefore, an MFA might be carried out for all the ships together. In that case, the spatial boundary still remains the same (i.e. the ship recycling yard) but the temporal boundary must be determined on the basis of the time frame for which the analysis is to be carried out. Material composition data must also be available in an aggregate form for all the ships that would be recycled within the set time frame. Nevertheless, an MFA carried out on a ship-by-ship basis provides enough details to a ship recycling yard to visualize, plan, execute and improve its processes.

5.4.2 MFA scenarios

The flows of materials shown in the preceding MFA diagrams depict the ideal amount of materials that can be derived from the case ship for the assumptions made in this research. In the actual situation, the amount of each material that can be derived from the case ship depends on the recycling process employed. For example, amount of input material and percentages of the EVS and NEVS coming out of ‘separation’ sub-process may differ. Some amount of ferrous and non-ferrous material (in the form of a valve or pipeline covered with insulation) might also go into the ‘separation’ sub-process. There might be no EVS coming out of ‘removal of insulation, flooring and tiling’ sub-process of the pre-cutting process depending on the demand of reusable insulation in the market and the possibility of removing insulation in good condition at a reasonable cost. For example, in India, intact glass wool insulation panels are purchased by resellers to cater the needs of cold storage firms and other industries requiring insulation material (Agarwal, 2015). Also, there is a strong demand of all the materials/products recovered from end-of-life ships by the network of secondary processing firms located around the ship recycling yards in Bangladesh (Crang et al., 2013, Gregson et al., 2012, Mizanur Rahman and Mayer, 2015). Endless scenarios and possibilities of material flows exist depending on the recycling process employed. The MFA can be used as a tool to visualize, plan, and compare different scenarios that can arise as a result of recycling an EOL ship. Few such scenarios describing the application of MFA on planning related tasks are illustrated by the following examples.

5.4.2.1 Case 1: decision making on reusable insulation

In certain cases, all the insulation originating from the EOL ship must be disposed, becoming a part of NEVS. For example, in certain ship recycling countries no market for reusable insulation exists; while on certain ships, insulation is glued to the ship structure and thus it is damaged in the removal process to such an extent that it cannot be sold in the second-hand market. In such scenarios, MFA diagrams of the ship recycling process would change drastically, altering the recycling costs and revenue generating capability of the sub-process 'removal of insulation, flooring and tiling' as shown in Figure 5.6.

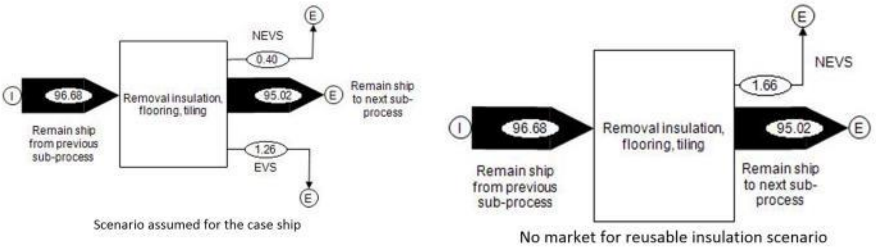


Figure 5.6: Material flowing in and out of the sub-process 'removal insulation, flooring and tiling' in two different scenarios

If scraping the insulation of a certain section of the steel hull is time consuming, the ship recycling yard might even consider throwing away the entire section of steel hull along with the insulation glued to it. In such case, certain portion of 95.02% of the remaining ship flowing to the next sub-process would also end up in the NEVS. The weight of such a hull portion (steel and insulation) flowing into NEVS depends on the area and thickness of the steel and insulation. Considering the relative thickness of the steel and the insulation on a typical bulk carrier, it can be concluded that a recycling yard would end up discarding 8 times the weight in steel, for each ton/percent of insulation. This results in 13.28% of LDT flowing into NEVS along with 1.66% of LDT for insulation. Such a scenario would result in a much bigger impact on the recycling yards' revenue generation than the scenario for the case ship (shown in Figure 5.6). The scenario shows a four times increase in NEVS, from 0.4% LDT to 1.66% LDT; while the throw-away-all scenario would lead to 37 times increase in the NEVS from 0.4% LDT to 14.94% LDT. For the case ship, the drop in revenue against today's material prices (USD 275 per ton of steel (Steelrates.com, 2015)) will be USD 400,000, allowing the yard to compare this figure with the costs of removal of the insulation glued to the steel. The drop in revenue due to no resale of insulation (USD 14,000 at an average rate of USD 100 per ton of glass wool insulation in the second hand market in India (Agarwal, 2015)) results from an unfavourable decision during the building phase of the vessel.

5.4.2.2 Case 2: calculating material handling capacity

The MFA diagrams show that the sub-process ‘removal of liquids’ require pumps to remove liquids weighing at least 1% of LDT (i.e. 110.44 T). The ship recycling yard must decide on the capacity and number of pumps that needs to be installed in order to pump out all the liquid in a requisite time frame. For example, a pump with a capacity of 5 T/hr would take 22 hours to pump out all the liquid from the case ship. 22 hours is an estimate that does not take into account the time required for rigging up of hoses and other preparatory work that must be carried out for each tank on a ship before starting to pump out the liquid. The preparatory work also involves gas-freeing and cleaning of tanks. These tasks are usually labour intensive. In some cases, liquid is in an unpumpable state, meaning that greater man power is required to scrape the sludge out of the tanks. The ship recycling yard can plan these tasks and make economically critical decisions such as number, capacity and parallel/consecutive operation of pumps on a per ship basis depending on the number and state of tanks on each ship.

5.4.3 Importance of applying MFA in ship recycling

It is established in this chapter that analytical tool MFA can be used by ship recycling yards to better plan the ship recycling process by establishing the flows of materials through different sub-processes taking place within a recycling yard. The flexibility of MFA as a tool in terms of spatial and temporal boundary settings makes it very useful, not only for planning and improving the ship recycling process on a particular yard for one or more ships but also for understanding and predicting the outputs of the ship recycling industry on the local, regional, national and global level.

The economic performance of a ship recycling yard can be improved by maximizing its revenue generation capability. Although MFA diagrams do not directly contribute to reducing recycling costs and increasing the revenue, they help determine the maximum revenue potential of recycling a number of ships within a particular time frame. Ship recycling yards can work on maximizing their revenue potential by finding ways to generate income from the waste anticipated to be generated as a result of recycling the EOL ships. For example, MFA can be used to compare waste management strategies such as landfill, waste to energy conversion, incineration, etc.

5.5 Conclusions

The green ship recycling yards are not very popular among a large number of ship owners due to their inability to offer a better price compared to yards which recycle ships in conditions dangerous to the environment and workers. Such yards can become competitive only when the price gap between the green and non-green recycling yards is reduced. This can only be done by increased revenue and reduced costs of green ship recycling yards. The upcoming regulations on ship recycling by European Union and International Maritime Organization focus on developing a unique ship recycling plan for every ship handled by a recycling yard. Such objectives of better planning the recycling process, reducing recycling costs and improving revenues can be achieved by applying tried and tested methodologies, tools and techniques.

This chapter discussed the tools available within the field of production and environmental management that are potentially applicable to the ship recycling industry for achieving its objectives. Even though ship recycling can be considered as reverse production, analytical tools used for environmental management are a natural fit due to the involved waste and environmental management issues. MFA has emerged as an important tool that can improve ship recycling and materials and waste management at ship recycling yards by determining the earning potential of each project as well as planning the utilization of resources (such as man power, machines and equipment) to attain maximum revenue.

This chapter explained the importance of applying MFA to the ship recycling industry. It can be used by recycling yards for visualizing and understanding the material flows within the recycling process, for comparing the status quo with different recycling scenarios, as a decision making tool to decide on waste management strategies, as a calculation tool to determine the amount of material generated for disposal and recycling, and as an analytical tool to plan the recycling process by calculating required material handling capacity and anticipated recycling steps.

Based on tours of recycling sites and secondary literary sources, the chapter also defined a generic ship recycling process that can be used by a recycling yard to dismantle a dry cargo ship irrespective of the docking method employed. The only published article in scientific journals explaining a generic ship recycling process is Hiremath et al. (2015).

A shortcoming of using MFA as a planning tool on a ship recycling yard is that it relies extremely on the input data. This data, in most cases, is either difficult to obtain or inaccurate. This can be overcome by improving the way information is passed to the recycling yards. The ship building yards should develop a document defining the material composition of ships in the form of a list of materials and their weights available on a ship. This is in line with the principle of extended producers’ responsibility. Such a document is easy to prepare during the ship design stage rather than at a later stage. It must also be updated during the ship’s lifetime as required by the Hong Kong convention for the Inventory of Hazardous Materials. Jain et al. (2016a) [Chapter 7] described how such a document can be developed (in the form of ship’s lightweight distribution) and added to the ship’s stability manual.

CHAPTER 6

ECONOMIC IMPACT ASSESSMENT MODEL[††]

"Anything that gives us new knowledge gives us an opportunity to be more rational."

- Herbert Alexander Simon (1916-2001), Economist

[††] The case study 1 of this chapter is reproduced from the paper submitted for peer-review to the journal, 'Resources, Conservation and Recycling' (ISSN: 0921-3449) and the case study 2 is reproduced from the paper submitted for peer-review in WMU Journal of Maritime Affairs (e-ISSN: 1654-1642).

As discussed in the introduction to this dissertation, the yards offering green ship recycling services cannot generally lure ship owners due to a lower offer price for buying end-of-life (EOL) ships than other yards. However, as discussed in Chapter 3, the waste generated by dismantling and recycling the EOL ships at these yards can become a potential source of income if a waste-to-energy technology such as plasma gasification is used. Such a waste management technology can turn waste into energy and other saleable products by managing waste environmentally friendlier than by means of burning or landfilling. The resulting income can be used to offer a higher price to the ship owners.

This chapter presents an economic analysis model to calculate the increase in offer price. The results show that the investment in a plasma gasification plant is earned back reasonably quickly; however, it may not allow the ship recycling yards to increase the offer price significantly enough to gain a substantial market share. The analytical model discussed in this chapter can also be used to calculate the change in offer price as a result of technological changes made to a recycling yard due to the application of international regulations such as the HKC and EUSRR. Therefore, this chapter discusses two case studies; first, the change in offer price as a result of plasma gasification plant and second, the change in offer price due to improved infrastructure of recycling yards to meet the criteria of the Hong Kong convention.

6.1 Case study 1

6.1.1 Introduction

The study begins with a brief overview of the ship recycling industry (Section 6.1.1.1), followed by a concise discussion on the availability of various waste-to-energy technologies and the suitability of plasma gasification technology with respect to the ship recycling related waste (Section 6.1.1.2). Based on the discussion in Sections 6.1.1.1 and 6.1.1.2, Section 6.1.1.3 describes the objectives of the research undertaken in this case study.

6.1.1.1 Ship recycling industry

Every year, thousands of ships are dismantled at the end of their useful lives at ship recycling yards around the world (Choi et al., 2016). On average, the materials and components that can be reused or recycled after being extracted from the end-of-life ships weigh about 96% of the weight of a ship (McKenna et al., 2012). Although this activity is useful for recycling materials such as steel, non-ferrous metals, etc.; it still generates a huge amount of waste which must be treated carefully before disposal. For example, in 2015, the total weight of the ships dismantled globally was 7 million tons (Robindesbois.org, 2015) and assuming that the waste generated is 5% to 10% of the weight of the ship (Demaria, 2010), a total of 350,000 to 700,000 tons of waste must have been generated on ship recycling yards around the world.

[As discussed in Chapter 2] Since most recycling yards are located in developing countries such as India, Pakistan, Bangladesh and China, where the enforcement of environmental regulations is lenient, a lot of waste (including hazardous) is not contained and released into the atmosphere polluting beaches, soil, water and air impacting the flora and fauna of the region, as discussed by several authors including Abdullah et al. (2013), Chang et al. (2010), Demaria (2010) and Okay et al. (2014), to name a few. However, the waste generated at the ship recycling yards complied with international HSE management systems and ship recycling regulations (such as EUSRR and IMO’s HKC) is generally sent to downstream waste management facilities for disposal. Such facilities include landfill sites, thermal waste treatment plants, incineration plants, etc. The recycling yards operating under such waste management policy are considered innocuous to the environment and health and safety of the workers, and are generally called ‘green’ ship recycling yards (Sarraf, 2010).

The treatment and disposal of waste by green ship recycling yards comes at an expense for such yards due to increased operating costs. Therefore, green recycling yards are unable to offer a higher price to ship owners for buying EOL ships as compared to other non-green/substandard yards. Since, most ship owners base their decision to select a recycling yard for selling their EOL ship on the price offered (Jain et al., 2017); green ship recycling yards have a limited amount of business in the ship recycling industry. For example, in 2012, the annual global green recycling capacity was just 780,000 tonnes (Abdullah et al., 2013) even though the total amount of ships recycled was recorded at about 11 million tonnes (Robindesbois.org, 2012). Such an extensive use of substandard yards undermines the contribution of the ship recycling industry towards sustainability. Therefore, there is an urgent need to improve the competitiveness of the green ship recycling yards.

The ability of a green ship recycling yard to offer a high price to ship owners for buying EOL ships can be improved when either the cost of recycling process is lowered or the revenue generated is increased. This chapter is focused at improving the revenue generated from the ship recycling process. As discussed before, the average amount of materials recycled from EOL ships is as high as 96% of the weight of a ship; there isn't much room to improve recycling rates for improving the revenues. Therefore, it is best to focus on the waste generated at the yards. The expenses for the waste disposal can be turned into revenues if a ship recycling yard is able to convert waste into useful products such as energy using certain waste-to-energy technologies. This revenue generation may allow a ship recycling yard to offer an increased price to a ship owner for buying an end-of-life ship for dismantling and recycling. An increased offer price may attract more ship owners and further stimulate green ship recycling.

6.1.1.2 Waste-to-energy technologies

Energy can be produced from solid waste using either biochemical, physiochemical or thermochemical treatment processes (Arena, 2012). However, thermochemical treatment processes characterized by higher temperatures and conversion rates than the other two processes, are by far the most effective treatment processes utilized by successfully operating waste management systems globally (Arena, 2012, Brunner et al., 2004, Porteous, 2005, Psomopoulos et al., 2009). Such waste management systems utilize either combustion, pyrolysis, gasification or the combination of these three to convert the energy value of waste into different energy forms such as electricity and process heat (Arena, 2012). However, gasification is considered to have several advantages over the other two thermochemical processes, mainly related to the product composition of the processes (Tang et al., 2013) and the possibility of combining the operating conditions and the features of the specific reactor (Arena, 2012). For example, incineration is associated with the generation of hazardous emissions such as SO_x, NO_x, chlorinated dioxins and furans, and pyrolysis is associated with low gas productivity and the wide spectrum of the decomposition products, which is difficult to overcome due to the slow rates of heating and cooling (Tang et al., 2013).

Standard gasification technologies operate the reactor in the range of 400 °C to 850 °C. At such low temperatures, all materials cannot break down at the molecular level; therefore this process produces a 'dirty' fuel gas, which contains tars, char and soot, weighing up to 15% of the weight of the incoming material (Mountouris et al., 2006). However, on the contrary, high temperature gasification can convert solid waste into useful products such as vitrified glass, reusable metal and synthesis gas (syngas), which can be used to produce energy through generators, gas turbines and boilers (Bosmans et al., 2013, Pourali, 2010). The syngas produced can also be used as feedstock in Fischer–Tropsch process for liquid fuel production or chemical products such as ammonia, methanol and hydrogen (Fabry et al., 2013). By doing so, pollutants emission could be reduced to almost zero and valorisation of all the components of waste could be achieved (Li et al., 2016a) because due to the high temperatures involved, all the tars, char and dioxins are broken down and almost all the carbon is converted to syngas (Mountouris et al., 2006).

The use of thermal plasma to initiate the gasification reactions is considered ideal for waste treatment applications because of its ability to provide high temperature (up to 15,000 °C), high intensity and energy density, and high non-ionising radiation (useful to destroy highly toxic compounds) (Ruj and Ghosh, 2014). The technical feasibility of the plasma technology to gasify different types of wastes, both hazardous and non-hazardous, is proven by Gomez et al. (2009). The recent advancement of the plasma technology with respect to waste disposal is discussed in Digman et al. (2009), which focused on ‘novel techniques’ to find solutions to concerns related to the gasification process and liquefaction and conversion of syngas to products such as ethanol and methanol, and in Tang et al. (2013), which emphasized on reactor designs.

The commercially available gasification technologies for waste-to-energy plants for the cogeneration of heat and power from syngas are discussed in Arena (2012), which found that there are more than 20 companies worldwide which have more than 100 gasifiers in operation and offer a commercially proven gasification process for different kinds of solid wastes. Similarly, Fabry et al. (2013) listed around 30 existing and upcoming plants for the gasification of waste by plasma. This includes several plants running commercially successfully, some of which are operating as early as since 1997 on different types of feedstocks including MSW, waste water sludge, ASR, hazardous waste, industrial waste and ship board waste. Thus, it is clear that a plasma gasification plant can be tailor-made to run on a particular type of feedstock. The existing plants are located in different locations, including the UK, US, India, China, Japan, Korea, France and other European countries (Arena, 2012, Fabry et al., 2013, Li et al., 2016a).

6.1.1.3 Research objectives

In this case study, we discuss the suitability of the waste generated at a ship recycling yard as a feedstock to a plasma gasification plant. The use of plasma gasification plant on a ship recycling yard will contribute to the sustainable development of our society by converting waste into energy and other useful products without burdening the environment, as opposed to regular waste burning (Danthurebandara et al., 2015).

The plasma gasification technology is capital intensive; therefore, not many owners of the ship recycling facilities would be interested in investing in it. The reluctance to invest may be due to the fact that the ship recycling business depends on the supply of end-of-life (EOL) ships, which is not always steady (Stopford, 2009). The supply of ships depends on the economic cycles of the shipping industry. During a recession, when there is not much demand for ships to carry cargo, ship owners decide to scrap obsolete ships increasing the supply to the recycling yards. On the contrary, during an economic boom, not many ships are available for scrapping because there is a huge demand for ships for maritime transport. A fluctuating supply of ships for recycling affects the waste generation at the ship recycling yards, which, in turn, will affect the operation of the plasma gasification plant. However, an economic analysis of installation and operation of a plasma gasification plant on a ship recycling facility may help its owner in the decision making on the basis of the scientific facts.

A ship recycling yard using a plasma gasification plant may attract ship owning companies that believe in CSR and environmentally friendly disposal of ships; whereas few other companies may be attracted if the offer price to buy an EOL ship is better than other recycling yards operating in the market. Therefore, the objective of this study is to quantify the change in offer price that may result due to the use of a plasma gasification plant on a ship recycling yard. The change in offer price is calculated for certain cases (discussed later) using an economic analysis model defined in the next section of this chapter.

Since sufficient waste is required to make a gasification plant economically viable, the number of suitable yards is therefore limited to a few of the largest recycling yards in the world, most of which are located in China. Therefore, a ship recycling yard of an annual dismantling capacity of 1 million tonnes is considered as a reference yard in this research. Since, almost all large green recycling yards are located in China; presently, the results obtained in this research can unfortunately be seen in the context of Chinese recycling yards only. However, this study can form the basis upon which a similar study can investigate the feasibility of operating a plasma gasification plant on yards located in other parts of the world.

6.1.2 Methods and data

This section begins with defining the method used to estimate the daily amount of waste generated on the reference yard (Section 6.1.2.1). The assumptions based on which the waste quantification is carried out are also discussed. The method used to determine the capital cost, operating cost and earnings of a plasma gasification plant is described in Section 6.1.2.2. The economic analysis model developed to quantify the change in offer price of EOL ships is defined in Section 6.1.2.3. Finally, the limitations of the research are discussed in Section 6.1.2.4.

6.1.2.1 Waste quantification

The amount of waste generated on a yard depends on the number, size and types of ships recycled. It is also affected by the rate of recycling, which depends on the material composition of the ship, technology employed by the yard, availability of downstream market for re-useable/recyclable products, applicable laws, etc. Therefore, it is difficult to accurately quantify the amount of waste generated at a particular ship recycling yard.

Due to such reasons, certain assumptions are required to be made to carry out this study. Firstly, as stated earlier, a recycling yard of 1 million tonnes annual recycling capacity is considered as a reference yard. Secondly, the material composition of a bulk carrier (weighing 11,044 tonnes) determined by Jain et al. (2017) is used in this study (Table 6.1). Thirdly, it is assumed that the material composition of all the ships recycled by the ship recycling yard being analysed is similar to that of the bulk carrier. Finally, the maximum and minimum recycling rates of 96.6% and 91.8% respectively are considered based on the following discussion.

The maximum recycling rate (96.6%) depicts an optimistic recycling scenario based on the flow analysis conducted by Jain et al. (2017), where a low amount of waste is generated; whereas the minimum recycling rate (91.8%) depicts a pessimistic recycling scenario, where a high quantity of waste is generated due to fewer possibilities for selling reusable/recyclable items in the market. The pessimistic recycling scenario assumes that everything except the ferrous scrap, non-ferrous scrap and machinery derived from an EOL ship is waste. The possibility of having a recycling rate lower than 91.8% does not exist because ferrous scrap, non-ferrous scrap and machinery scrap is hardly discarded as waste in any part of the world. Together, they comprise 91.8% of the weight of the ship considered in this study (Table 6.1). Similarly, the possibility of having a higher recycling rate than 96.6% is hard to imagine because the reference study (Jain et al., 2017) showed that in principle the remaining amount of materials (3.4%) are polluted or hazardous materials.

Table 6.1: Material Composition of the bulk carrier as calculated by Jain et al. (2017) and the assumptions for the classification of its components into organic, inorganic and liquid content.

S.no.	Components of the material composition	Classification
1.	Ferrous	Not a part of waste
2.	Non-ferrous	Not a part of waste
3.	Machinery	Not a part of waste
4.	Electrical and electronics	Not a part of waste
5.	Minerals	Inorganic (50% by weight not a part of waste)
6.	Plastics	Organic
7.	Liquids	Liquid
8.	Chemicals and Gases	Organic
9.	Joinery	Organic
10.	Miscellaneous	50% each organic and inorganic

Therefore, for our reference yard, the amount of waste generated at maximum and minimum recycling rates possible (as assumed in this study) can be calculated as 93.15 TPD and 224.66 TPD, respectively (Table 6.2). Based on these results, the maximum and minimum capacity of the plasma gasification plant required on a ship recycling yard of 1 million T annual recycling capacity is approximately 225 TPD and 90 TPD respectively. Therefore, two types of plasma gasification plants – 250 TPD and 100 TPD are analysed in this chapter, assuming the 10% capacity reduction due to planned and unplanned maintenance (based on the discussions carried out in literature (Arena, 2012, Cyranoski, 2006, Ducharme, 2010, Fabry et al., 2013)). The ship recycling yards of various other dismantling capacities can also generate the same amount of waste at different recycling rates falling within the range considered in this research (Table 6.3). Therefore, in addition to the reference yard, such yards are also considered for the analysis of the change in offer price. The idea is to see to what extent a plant of 250 or 100 TPD capacity is viable for recycling yards of different dismantling capacities, rather than to narrowly identify the benefits of a specific plant size for each yard (see Table 6.2).

The interval of 250,000 TPY yard size (Table 6.2) allows us to vary yard size, in reference to the reference yard, by the most relevant minimum annual dismantling capacity of a yard for the case studied in this research. The yard sizes of more than 1.5 million TPY do not exist presently and might be practically impossible to operate, and the yard sizes of 250,000 TPY do not produce sufficient waste for the plasma gasification plants considered in this research (see Table 6.2). Therefore, they are not considered for the analysis. However, the yard size of 2 million TPY is still considered for the analysis to get an insight into a future large sized yard, considering the ever increasing sizes of merchant ships.

Table 6.2: The amount of waste generated (in TPD) by different sized yards at assumed maximum and minimum recycling rates.

Yard size (TPY)	Waste generated at maximum recycling rate (96.60%)	Waste generated at minimum recycling rate (91.80%)
250,000	23.29	56.16
500,000	46.58	112.33
750,000	69.86	168.49
1,000,000	93.15	224.66
1,250,000	116.44	280.82
1,500,000	139.73	336.99
2,000,000	186.30	449.32

Table 6.3: Recycling rates at different sizes of yards for 100 TPD and 250 TPD plasma gasification plants.

Yard size (TPY)	100 TPD plant	250 TPD plant
500,000	93.20%	Out of range
750,000	95.50%	Out of range
1,000,000	96.60%	91.80%
1,250,000	Out of range	93.40%
1,500,000	Out of range	94.50%
2,000,000	Out of range	95.90%

6.1.2.2 Determination of capital costs, operating costs and earnings

The capital cost of a plasma gasification plant depends on its size. Based on the capital costs of several plasma gasification plants around the world, Byun et al. (2012) developed a capacity (TPD) vs capital cost (million US$ per TPD) plot. The average capital cost for a 250 TPD plant ranges from 0.17 to 0.22 million $/T, whereas for a 100 TPD plant it is about 0.25 million $/T (Byun et al., 2012). Therefore, the average capital cost of a 250 TPD plant and a 100 TPD is $48,750,000 and $25,000,000, respectively.

The earnings of a plasma gasification plant mainly depend on the sale of electricity generated using the syngas produced, which basically means energy recovery from the waste. The moisture content, chemical composition and the calorific value of the feedstock have significant impact on the process of energy recovery due to the following reasons (Ducharme, 2010). The high moisture content significantly lowers the efficiency of the gasification process. The amount of organic and inorganic fraction in the waste determines the amount of syngas and slag produced as the organic content is converted into syngas and the inorganic content is converted into slag. The calorific value denotes the chemical heat content of the waste (in kWh), which is the basis of the amount of syngas/electricity produced. For example, feedstock having 10 MJ/kg calorific value, corresponding to 2800 kWh chemical heat for a ton of feedstock, will produce 2800 × 25% = 700 kWh electricity, considering 25% thermal efficiency of the plant.

Table 6.4: Chemical composition of the MSW and the waste generated at the ship recycling yard (SRY).

	Municipal solid waste (Ducharme, 2010)	Waste generated at the SRY (Calculated based on (Jain et al., 2017) and Table 6.1)
Organic content	60%	61%
Inorganic content	20%	30%
Liquid content	20%	9%

The chemical composition of the waste generated on a yard can only be determined by conducting certain chemical tests such as ultimate and proximate analysis on the waste samples, which is out of the scope of this study. Therefore, a preliminary ‘table-top’ assessment of the material composition of the bulk carrier (discussed above) is carried out. The assessment is based on the material composition of the bulk carrier calculated by Jain et al. (2017) and the classification of each of its component into organic, inorganic and liquid content (refer Table 6.1). The assessment found that the organic, inorganic and liquid content of the waste generated on the ship recycling yard is similar to that of the MSW studied by Ducharme (2010) (refer Table 6.4), a study referred in this research to determine the operating costs and earnings data of plasma gasification plants.

The values of MSW composition, operating costs and annual earnings may differ from study to study depending upon the location where the study is carried out, assumptions undertaken and several other parameters. However, we consider that a ballpark figure is sufficient to understand the impact of a plasma gasification plant on a large ship recycling yard. A slight upward or downward change in these values may not change the results of this research significantly. Therefore, we consider the values of Ducharme (2010) as the best available estimate despite the fact that the calorific value of the MSW studied by Ducharme (2010) is 10 MJ/kg, whereas the calorific value of the waste generated by recycling yards, based on Reddy et al. (2005), is calculated as 20.37 ± 1.17 MJ/kg. We consider that these values can help analyse a pessimistic scenario (low calorific value of the waste) while an optimistic scenario (high calorific value of the waste) can be analysed by using the increased annual earnings, as discussed in the next section.

In addition to the difference in the numbers of calorific values, the values of inorganic and liquid content of the waste generated on the ship recycling yard also differ from the reference study (Table 6.4). However, it will not have any adverse effect on the revenue generated because the lower value of moisture content will improve the efficiency of the gasification process and the higher value of inorganic content will increase the amount of slag production, thereby revenue. Therefore, based on Ducharme (2010), the earnings per ton of the waste processed are calculated by subtracting the operating expenses ($53 per ton) from the revenue generated ($121.32 per ton), which is therefore calculated as $68.32 per ton. The annual earnings at 90% operating capacity can be calculated as ‘x’ TPD × 0.9 × 365 × 68.32, which is therefore calculated as $5,610,780 and $2,244,312 for 250 TPD plant and 100 TPD plant, respectively.

6.1.2.3 Quantifying the change in offer price

The offer price to buy an EOL ship can be increased if a ship recycling facility generates increased earnings as a result of using the plasma gasification plant and uses them to offer an increased amount to the ship owners. Therefore, the profitability of the plasma gasification plant must be determined. The profitability of an investment project can be determined using the concept of IRR (Hagemann, 1990). Since IRR does not take into account the time value of money, some analysts prefer to use NPV as a metric to decide whether to invest in a project or not. However, IRR is considered a suitable metric when two or more projects are not compared to each other and a project is tested for feasibility only. Therefore, IRR is used in this study. Mathematically, the IRR is defined as the interest rate that equates the present worth of a series of cash flows to zero (Hartman and Schafrick, 2004). It defines the return achieved by an investment. The higher the IRR of a project, the higher will be the profitability.

The decision on pursuing an investment can be taken by comparing the IRR to the discount rate. The discount rate is also called as the cost of capital, marginal growth rate, hurdle rate and MARR (Hartman and Schafrick, 2004). The discount rate is generally established by a company depending on its risk tolerance and other market related factors such as the cost of borrowing, interest rates, tax, depreciation, etc. The investment project having the IRR greater than the MARR can be accepted. In such a scenario, the cash flow at IRR would certainly be higher than the cash flow at MARR. In this chapter, we propose that the difference between the two cash flows is utilized by a ship recycling yard to offer an increased sum of money to the ship owners for buying EOL ships. This may help a ship recycling yard to increase its market share by attracting ship owners with a promising offer price.

Therefore, the difference between the cash flows at IRR and MARR is the amount that is available per year for offering a higher price to buy an EOL ship. This amount divided by the annual recycling capacity of the yard calculates the change in offer price per ton of the weight of the ship. The cash flow at IRR is the annual earnings of a plasma gasification plant (section 6.1.2.2), whereas the cash flow at MARR is calculated using a model developed in Microsoft Excel, which uses its ‘goal-seek’ function to calculate the free cash flow at a given discount rate. The IRR is calculated considering the lifetime of the plasma gasification plant as 20 years as mentioned in some of the feasibility studies of the plasma gasification plants (Clark and Rogoff, 2010, Dodge, 2008). The cash flows from year 1 to 20 are assumed same (annual earnings calculated in section 6.1.2.2), while the cash flow at year 0 is the capital cost (negative) of the plant. The calculation model is further explained in Appendix A.

Furthermore, the what-if analysis is carried out to analyse the change in offer price at various discount rates depicting the different scenarios. The similar analysis is carried out for different scenarios of increased annual earnings (which changes the IRR and the cash flow at IRR) to account for the increase in revenue due to increased calorific value of the waste as discussed in section 6.1.2.2 and the approximations made by Ducharme (2010) in calculating the revenue and operating expenses of a plasma gasification plant.

6.1.2.4 Limitations of the study

The study conducted in this chapter has following limitations, most of which are attributed to the limited data availability:

1. The study is limited to only two sizes of the plasma gasification plant, even though in some of the scenarios considered, other sizes of plants may be required (Table 6.2).
2. The study is limited to only plasma gasification process even though other thermochemical processes may also be utilized on the ship recycling yards. However, reasons to study plasma gasification are explained clearly.
3. The use of ballpark figures for capital costs, operating costs and earnings generated from the gasification plant provides approximate results. However, no significant impact on the results is anticipated.
4. The material composition data of just one ship is used to quantify the waste generated at the recycling yard due to the lack of availability of relevant data from recycling yards.
5. All ships dismantled on the yard studied are considered similar to the case ship, which is not possible in a real life situation.
6. The effect on yard earnings from recyclable products due to varying recycling rates is not considered to simplify the calculations.

6.1.3 Results and discussion

This section of the case study is divided into three sub-sections. The IRR calculations of both 250TPD and 100TPD plants are discussed in Section 6.1.3.1, followed by the what-if analysis providing the results of increased offer price at various discount rates in Section 6.1.3.2. The scenarios arising due to uncertainty in the initial cash flow are discussed in Section 6.1.3.3.

6.1.3.1 Internal rate of return

The internal rate of return for 250 TPD and 100 TPD plants, considering the 20 years lifetime, is calculated as 9.70% and 6.36% respectively (Table 6.5). The IRR calculations show that a 250 TPD plant will start providing positive returns from the 9th year onwards while a 100 TPD plant will yield positive returns from the 12th year onwards. This clearly means that the concept of economies of scale is applicable to these plants. The higher the capacity of the plant, the better the returns are likely. However, there is a limit to the capacity of a plant that can be installed on a ship recycling yard depending on the amount of waste available as feedstock to the plant.

Table 6.5: IRR calculations for the plasma gasification plants.

	250 TPD plant		100 TPD plant	
	Cash flow	**IRR**	**Cash flow**	**IRR**
Year 0	-$48,750,000		-$25,000,000	
Year 1	$5,610,780	-88.49%	$2,244,312	-91.02%
Year 2	$5,610,780	-59.84%	$2,244,312	-65.21%
Year 3	$5,610,780	-38.87%	$2,244,312	-45.01%
Year 4	$5,610,780	-25.14%	$2,244,312	-31.28%
Year 5	$5,610,780	-15.98%	$2,244,312	-21.88%
Year 6	$5,610,780	-9.65%	$2,244,312	-15.25%
Year 7	$5,610,780	-5.13%	$2,244,312	-10.43%
Year 8	$5,610,780	-1.80%	$2,244,312	-6.82%
Year 9	$5,610,780	0.71%	$2,244,312	-4.07%
Year 10	$5,610,780	2.64%	$2,244,312	-1.92%
Year 11	$5,610,780	4.15%	$2,244,312	-0.21%
Year 12	$5,610,780	5.35%	$2,244,312	1.16%
Year 13	$5,610,780	6.32%	$2,244,312	2.28%
Year 14	$5,610,780	7.11%	$2,244,312	3.21%
Year 15	$5,610,780	7.76%	$2,244,312	3.97%
Year 16	$5,610,780	8.29%	$2,244,312	4.62%
Year 17	$5,610,780	8.74%	$2,244,312	5.16%
Year 18	$5,610,780	9.12%	$2,244,312	5.62%
Year 19	$5,610,780	9.43%	$2,244,312	6.02%
Year 20	$5,610,780	9.70%	$2,244,312	6.36%

In conclusion, the analysis shows that a 100 TPD plant is not promising to the owner of a ship recycling yard because it starts yielding positive returns much later than a 250 TPD plant (12 years against 9 years). Moreover, the 20 years of operation of a 100 TPD plant provides much lower rate of return (6.36%) than a 250 TPD plant (9.70%).

6.1.3.2 What-if analysis

The results shown in Table 6.3 indicate that the ship recycling yards of various dismantling capacities can generate close to 225 TPD and 90 TPD waste at different recycling rates. Therefore, such recycling yards can potentially implement the plasma gasification plants of capacities considered in this research. Hence, the what-if analysis at various discount rates is also carried out for such yards to determine the change in offer price. The results of what-if analysis of 250 TPD and 100 TPD plants on ship recycling yards of various annual dismantling capacities at different discount rates are presented in Table 6.6 and Table 6.7, respectively.

Table 6.6: What-if analysis of a 250 TPD plasma gasification plant on ship recycling yards of various dismantling capacities at different discount rates.

Cash flow at IRR	What-if IRR (MARR) is	Cash flow at MARR	Difference in cash flow	Change in offer price by ship recycling yards of 'x' annual dismantling capacity in million T per year			
				x =1.00	x =1.25	x =1.50	x =2.00
$5,610,780	0.50%	$2,567,490	$3,043,290	$3.04	$2.43	$2.03	$1.52
$5,610,780	1.00%	$2,701,497	$2,909,283	$2.91	$2.33	$1.94	$1.45
$5,610,780	2.00%	$2,981,390	$2,629,390	$2.63	$2.10	$1.75	$1.31
$5,610,780	3.00%	$3,276,766	$2,334,014	$2.33	$1.87	$1.56	$1.17
$5,610,780	4.00%	$3,587,110	$2,023,670	$2.02	$1.62	$1.35	$1.01
$5,610,780	5.00%	$3,911,826	$1,698,954	$1.70	$1.36	$1.13	$0.85
$5,610,780	6.00%	$4,250,247	$1,360,533	$1.36	$1.09	$0.91	$0.68
$5,610,780	7.00%	$4,601,655	$1,009,125	$1.01	$0.81	$0.67	$0.50
$5,610,780	8.00%	$4,965,295	$645,485	$0.65	$0.52	$0.43	$0.32

Table 6.7: What-if analysis of a 100 TPD plasma gasification plant on ship recycling yards of various dismantling capacities at different discount rates.

Cash flow at IRR	What-if IRR (MARR) is	Cash flow at MARR	Difference in cash flow	Change in offer price by ship recycling yards of 'x' annual dismantling capacity in million T per year		
				x=1.00	x=0.75	x=0.50
$2,244,312	0.50%	$1,316,661	$927,650	$0.93	$1.24	$1.86
$2,244,312	1.00%	$1,385,383	$858,929	$0.86	$1.15	$1.72
$2,244,312	2.00%	$1,528,918	$715,394	$0.72	$0.95	$1.43
$2,244,312	3.00%	$1,680,393	$563,919	$0.56	$0.75	$1.13
$2,244,312	4.00%	$1,839,544	$404,768	$0.40	$0.54	$0.81
$2,244,312	5.00%	$2,006,065	$238,247	$0.24	$0.32	$0.48
$2,244,312	6.00%	$2,179,614	$64,698	$0.06	$0.09	$0.13

The results in Table 6.6 show that a ship recycling yard of annual dismantling capacity of 1 million tonnes per year can offer a maximum increase of $3.04 per ton of the weight of the ship (at 0.50% MARR) by employing a 250 TPD plasma gasification plant. However, the minimum MARR considering the interest rates and other market parameters can be considered 5% (Meier and Tarhan, 2007).

Therefore, considering the most realistic market conditions, a ship recycling yard of 1 million tonnes annual dismantling capacity can offer a maximum increase of \$1.70 per ton of the weight of the ship by employing a 250 TPD plasma gasification plant.

The results in Table 6.7 show that a ship recycling yard of annual dismantling capacity of 1 million tonnes per year can offer a maximum increase of mere \$0.93 per ton of the weight of the ship (at 0.50% MARR) by employing a 100 TPD plasma gasification plant. At 5% MARR, which is considered the most reasonable MARR, an increase of just \$0.24 per ton of the weight of the ship can be offered.

The results presented in Table 6.6 and Table 6.7 shows that a 250 TPD plasma gasification plant allows a larger increase in offer price than a 100 TPD plasma gasification plant. The increase in offer price due to a 100 TPD plant is significantly low and investment in it is not favourable to a ship recycling yard. Therefore, it may not be able to lure the potential ship owners towards the environmentally friendly ship recycling. On the other hand, the increase in offer price due to a 250 TPD plant, although not very high, can still lure the potential ship owners because it is financially attractive to ship recycling yards, which ensures its operability, and it provide ship owners with some amount of extra money for recycling their ships in an environmentally friendly manner. For example, recycling an 11,044 T handymax bulk carrier at a yard of 1 million T per year dismantling capacity can fetch about \$18,000 extra, if 5% MARR is assumed.

The increase in offer price (\$ per ton of the weight of the ship) due to the use of 250 TPD and 100 TPD plasma gasification plants by ship recycling yards of various annual dismantling capacities at different discount rates is depicted by Figure 6.1 and Figure 6.2 respectively (based on Table 6.6 and Table 6.7).

The fact that the use of a 250 TPD plant can increase the offer price more than a 100 TPD plant can be inferred as a negative relationship between the recycling rate and the increase in offer price because lower the recycling rate higher the waste generated and the required capacity of the plasma gasification plant. However, it cannot be concluded that a ship recycling yard must reduce the recycling rate to increase the offer price. This is due to the fact that in certain countries, recycling or reusing certain items derived from the EOL ships may fetch more revenue than discarding them as waste and feeding in a plasma gasification plant. This depends on how buoyant the downstream market is and how much money can be earned by selling such items in the market.

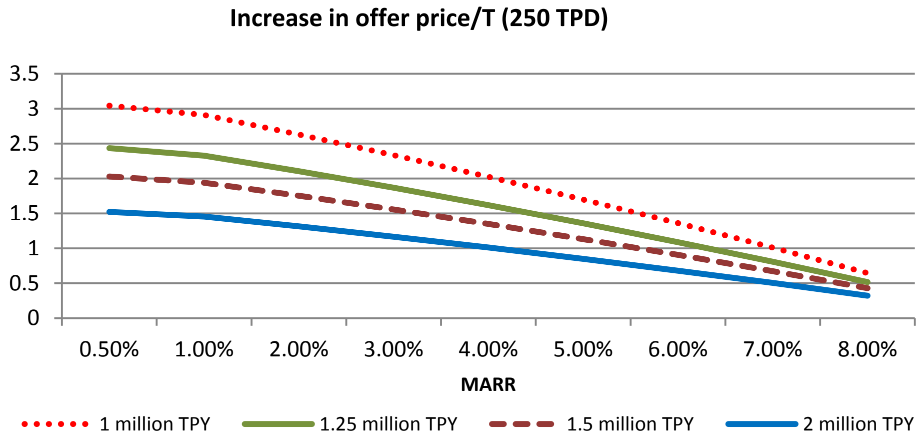


Figure 6.1: Increase in offer price ($/T) due to 250 TPD plasma gasification plant operated at different sizes of recycling yards at various discount rates.

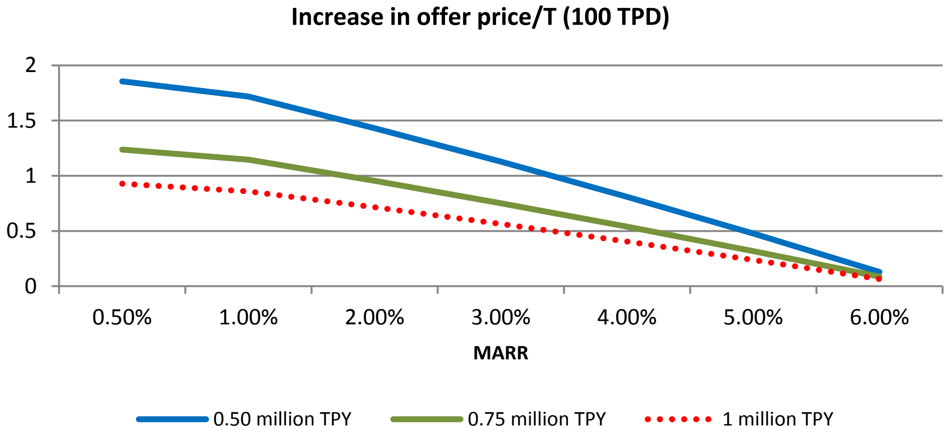


Figure 6.2: Increase in offer price ($/T) due to 100 TPD plasma gasification plant operated at different sizes of recycling yards at various discount rates.

A closer look at the results of Table 6.6 and Table 6.7 reveals that smaller the yard size (dismantling capacity in TPY) greater the increase in offer price. However, it is not advisable for yards to reduce their dismantling capacity to increase the offer price using a plasma gasification plant because the reason for such results is the fact that the sizes of plasma gasification plants are considered constant, which means that the comparison is being made at different recycling rates (mentioned in Table 6.3). In order to compare different yard sizes, plasma gasification plants required to manage the waste generated at the maximum and minimum recycling rates of various yards (Table 6.2) must be compared and analysed. However, it is not carried out in this chapter because the entire procedure will be repetitive and more importantly, the results can be anticipated on the basis of the numbers of the capital costs of the plasma gasification plants. As discussed in Section 6.1.1.2, high capacity plants have comparatively low capital costs per TPD. Certainly, they will also be more profitable to operate and will result in a greater increase in offer price (as also verified by comparing the results of 250 TPD and 100 TPD plants).

6.1.3.3 Scenarios due to uncertainty in the initial cash flow

The annual earnings of the plasma gasification plants are based on the assumptions and approximations discussed in Section 6.1.2.2. The uncertainty regarding the calorific value of the waste also affects the earnings. Therefore, it is wise to carry out the analysis for the change in offer price by varying the annual earnings. This study analyses the change in offer price for 250 TPD and 100 TPD plants with two scenarios of change in initial cash flow, i.e., 50% and 100% increase to the cash flow. This increase in the initial cash flow will also impact the IRR positively. For example, the IRR due to 100% increase in cash flow for 250 TPD and 100 TPD plants will be 22.63% and 17.20%, respectively. Similarly, the IRR due to 50% increase in cash flow will be 16.44% and 12.09% for 250 TPD and 100 TPD plants, respectively.

The what-if analysis of the two scenarios of change in initial cash flow is presented in an appendix (Appendix B, Appendix C, Appendix D and Appendix E). Based on such analysis, increase in offer price by using 250 TPD and 100 TPD plasma gasification plant for various sizes of the ship recycling yards at different discount rates is depicted by Figures 6.3, 6.4, 6.5 and 6.6. The analysis at 5% MARR shows that a 50% increase in the initial cash flow would allow a ship recycling yard of 1 million tonnes annual dismantling capacity to offer an increase of $4.50 per ton of the weight of the ship if a 250 TPD plasma gasification plant is used, whereas an increase of just $1.36 per ton of the weight of the ship is possible if a 100 TPD plasma gasification is used. On the other hand, a 100% increase in the initial cash flow would allow the same recycling yard to offer an increase of $7.31 per ton of the weight of the ship with a 250 TPD plasma gasification plant, whereas the increase with a 100 TPD plant is $2.48 per ton of the weight of the ship.

The maximum increase in the offer price is possible at 0.5% MARR and 100% increase in the initial cash flow, when a ship recycling yard of 1 million tonnes annual dismantling capacity can offer an increase of $8.65 per ton of the weight of the ship using a 250 TPD plasma gasification plant. With a 100 TPD plant, this increase in offer price is $3.17 per ton of the weight of the ship.

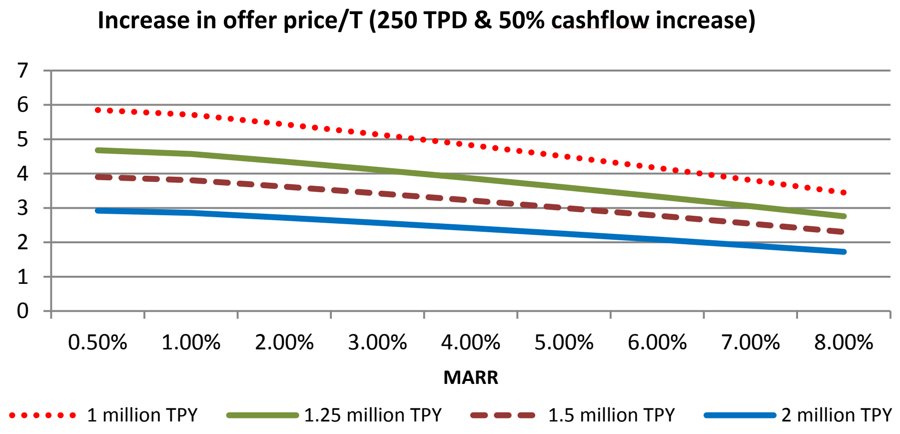


Figure 6.3: Increase in offer price ($/T) due to 250 TPD plasma gasification plant operated at different sizes of recycling yards at various discount rates, considering a 50% increase in the initial cash flow.

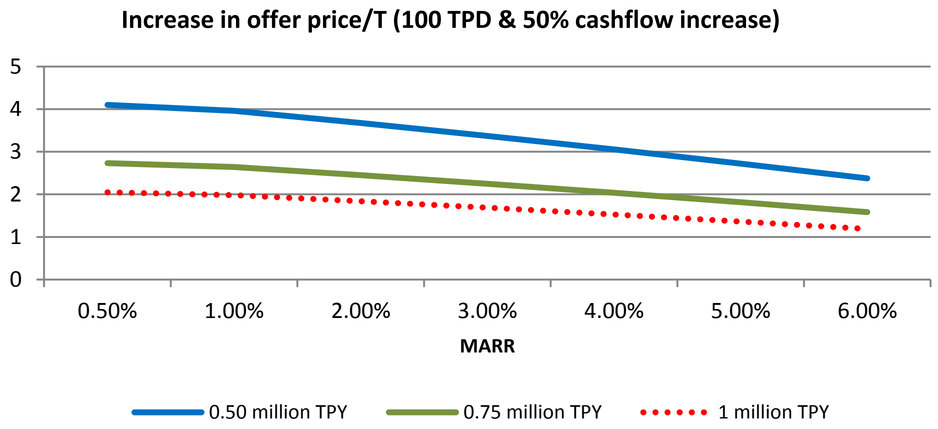


Figure 6.4: Increase in offer price ($/T) due to 100 TPD plasma gasification plant operated at different sizes of recycling yards at various discount rates, considering a 50% increase in the initial cash flow.

However, since 0.5% MARR is not realistic, it can be concluded that a maximum increase of $7.31 per ton of the ship's weight is possible using a 250 TPD plant on a ship recycling yard of 1 million tonnes annual dismantling capacity, whereas with a 100 TPD plant a maximum increase of $2.48 per ton of the ship's weight is possible.

An important scenario for this study could be a case where one plasma gasification plant caters to a group of yards. In such a scenario, a plant of very large capacity, say 1000 TPD, can be installed. This will provide a reduction in capital costs due to economies of scale. However, the earnings from the plant will be divided between the yards feeding the plant. The preliminary findings of such a scenario do not show any evidence of being beneficial to the offer rate than the scenarios considered here. Therefore, it is not included in this study.

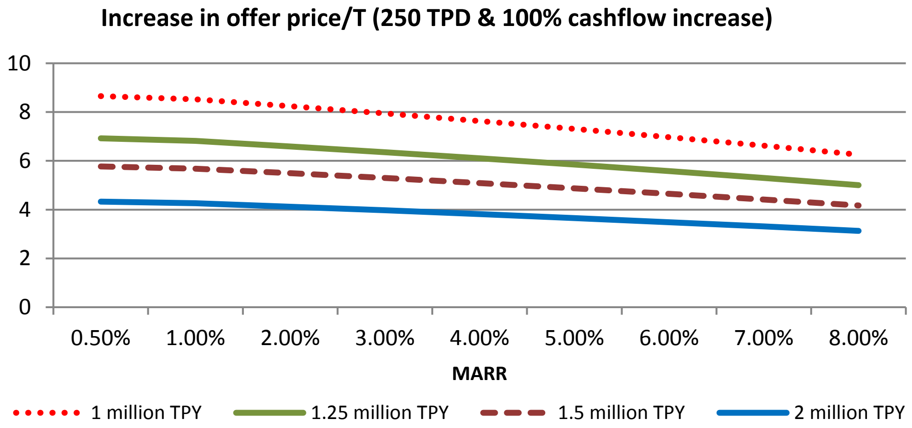


Figure 6.5: Increase in offer price ($/T) due to 250 TPD plasma gasification plant operated at different sizes of recycling yards at various discount rates, considering a 100% increase in the initial cash flow.

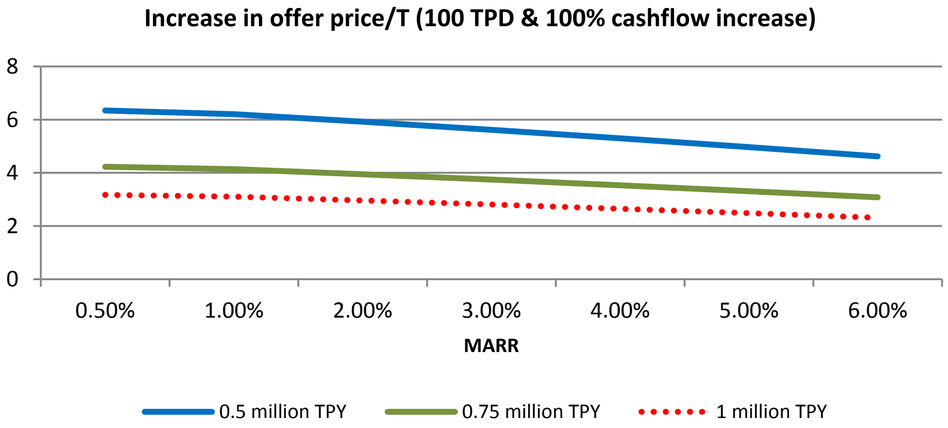


Figure 6.6: Increase in offer price ($/T) due to 100 TPD plasma gasification plant operated at different sizes of recycling yards at various discount rates, considering a 100% increase in the initial cash flow.

6.1.4 Conclusions

The research presented in this chapter aims to attract the attention of the ship recycling industry towards a technology that can potentially play a constructive role in managing the waste generated on ship recycling yards due to the dismantling of end-of-life ships. Therefore, this chapter presented a model to conduct an economic analysis of using a plasma gasification plant on a large ship recycling yard. The use of a plasma gasification plant will allow ship recycling yards to convert waste into useful products, which, in turn, will generate income for them. This income can be used to offer an increased amount to buy the EOL ships for dismantling and recycling.

The analysis carried out in this chapter suggests that the quantity of the waste generated at a ship recycling yard of 1 million tonnes annual dismantling capacity would range from 93 to 225 TPD. Therefore, two plasma gasification plants of 250 and 100 TPD capacities were analysed for the increase in price that may be offered to buy the EOL ships. The plant capacities analysed in this chapter take into account the downtime required for the planned and unplanned maintenance.

The profitability of a 250 TPD plant is better than that of a 100 TPD plant as determined by the internal rate of return calculated for a lifetime of 20 years. The IRR is calculated as 9.70% and 6.36% for a 250 TPD and 100 TPD plant, respectively. Moreover, a 250 TPD plant starts yielding a positive return after 9 years against 12 years for a 100 TPD plant.

The results show that the use of a 250 TPD plant would allow a large ship recycling yard (1 million tonnes annual dismantling capacity) to offer an increase of $1.70 per ton of the ship’s weight, whereas the use of a 100 TPD plant would let it offer just an increase of $0.24 per ton of the ship’s weight, at 5% minimum accepted rate of return.

The study also analysed the increase in offer price at 50% and 100% increase in the annual earnings of the plants to account for the assumptions and approximations considered in determining the earnings, especially regarding the calorific value of the waste. A 50% increase in the earnings of a 250 TPD plant would allow a large ship recycling yard to offer an increase of $4.50 per ton of the ship’s weight, whereas a 100% increase would allow an increase of $7.31 per ton of the ship’s weight at 5% MARR. The values for a 100 TPD plant are $1.36 and $2.48 per ton of the ship’s weight at 50% and 100% increase in the earnings respectively.

Although the use of a plasma gasification plant on a ship recycling yard does not offer a substantial increase in the price to buy the EOL ships, it may attract certain ship owners to recycle their ships in an environmentally friendly manner with a small amount of extra money on offer. The ship owners particularly interested in environmentally friendly initiatives might become interested in recycling their EOL ships at the yards employing a plasma gasification plant.

6.2 Case study 2

6.2.1 Introduction

As discussed in Chapters 1 and 2, the aim of the HKC is to ensure that the ships do not pose hazards to the environment, human health and safety during recycling operations carried out at the end of their economic lives. The convention regulates both the ships and the ship recycling facilities. It provides certain requirements for the operation of the ship recycling facilities so that the adverse effects of ship recycling to human health and the environment can be prevented and the hazardous materials originating from the EOL ships can be managed in a safe and environmentally sound manner (IMO, 2009).

The convention, although not yet in force, has led to the upgrade of several non-compliant yards to HKC-compliant yards following the investments made by yard owners for improving the infrastructure of the yards (Kagkarakis et al., 2016). Such investments will increase the operational costs of the yard as they will need to be paid and maintained. This in turn will stimulate yard owners to reduce the price offered to buy EOL ships if all other costs of the recycling process remain constant. Such practice of offering a reduced offer price is already prevalent in some of the new HKC-certified yards in India. This is verified by a personal communication to a higher management personnel of a recent HKC-certified yard in Alang, India (Agarwal, 2016a).

The aim of this case study is to quantify the reduction in offer price as a result of investments made to upgrade non-HKC-compliant yards. The four main investment scenarios are represented by the types of facilities. Therefore, the costs of upgrading an existing pier-breaking facility, an existing slipway facility, a basic pier, and a basic harbour to a HKC-compliant yard are considered. Each of these four scenarios are analysed with two variables in the form of annual recycling capacity and cost variability.

The categories of annual recycling capacities representing different yard sizes include the yards having the capacities of 100,000 lightweight per year (LDT/year), 50,000 LDT/year, and 25,000 LDT/year. The yard having an annual recycling capacity of 100,000 LDT represents an average sized recycling yard while the other two yards represent the smaller sized yards. The cost variability of each scenario due to the variations in the cost of recycling equipment and infrastructure is represented by high, baseline and low cost scenarios. The deliberation of three dimensions, i.e., facility type, recycling capacity and cost variability results in various scenarios available for analysis. Such scenarios are explained in detail in the next section of the chapter, which also explains the method used to calculate the reduction in offer price.

6.2.2 Methods and data

The reduction in offer price is calculated by using a Microsoft (MS) Excel based net present value (NPV) model re-engineered for the analytical problem considered in this research (Appendix A). The developed model uses the amount of investment made for upgrading a recycling facility as an input parameter. The model first calculates the annual cash flow that would be generated by the investment over a period of 20 years (lifetime of an infrastructure) using the ‘goal-seek’ function of MS Excel. The use of ‘goal-seek’ function to perform such calculations is discussed by several authors, such as Cahill and Kosicki (2000), Rao (2006) and Strulik (2004) to name a few. The discount rate of 5% is assumed for the calculation. As a result, the minimal annual cash flow ($/year) required to make the investment worthwhile (NPV=0) is calculated. This annual cash flow is divided by the annual recycling capacity of the yard (LDT/year) to calculate the reduction in offer price ($/LDT).

This method calculates the reduction in offer price because of the fact that no improvement in the earnings of a recycling yard is possible due to an upgrade, and therefore, the investment can only be paid for by reducing the price offered to buy the EOL ships. The assumption of a five percent discount rate and a zero NPV at the end of 20 years of the investment means the annual return on investment would be 5% if the calculated annual cash flow is achieved by the recycling yard as a result of its upgrade. The annual rate of return of five percent is a low value in these calculations as basically finance costs and minimal inflation is considered. The goal is not to estimate a profit (if any), but to estimate the effect on costs (and thus offer price) over the period of the investment.

6.2.2.1 Investment cost scenarios

The only study that provides the investment cost data is carried out by Overgaard et al. (2013) on behalf of the consulting company Litehauz for the United Nations agency called United Nations Environment Program (UNEP). It is used in this research to analyse the change in offer price due to upgrading of various types of recycling facilities. It considered four types of facilities to upgrade, out of which two are non-compliant ship recycling facilities and the remaining two are the sites where basic infrastructure (port facilities, quays, access roads) is in place but no recycling operations have been carried out. The former include an existing pier-breaking facility and an existing slipway facility, which are considered scenarios 1 and 2, respectively. The latter include a basic pier and a basic harbour, which are considered scenarios 1a and 2a, respectively. The upgrade of a beaching yard is thus not part of this research, but can be expected to be higher than the values assumed here.

The pier-breaking ship recycling method is primarily used in China, EU, and the U.S. In this method, the ship is secured to a pier in sheltered water, just like it is berthed on a port while discharging cargo (Choi et al., 2016). Generally, a gantry crane is used to remove parts of the ship until it can be lifted out of the water (Andersen et al., 2001). The slipway method of recycling ships is primarily used in Turkey. It is also called as landing or non-tidal beaching (Choi et al., 2016). In this method, the ship is pulled up onto a concrete slipway using winches. A mobile crane is typically used to remove the dismantled parts of the ship.

In this research, the baseline upgrade cost is considered for a dismantling capacity of 100,000 LDT/year. The upgrade cost for dismantling capacities of 50,000 LDT/year and 25,000 LDT/year is also estimated for all the scenarios. The low and high-cost scenario for each upgrade scenario is considered keeping in mind the changes in the cost of heavy machinery and dismantling equipment, and the cost of concrete and construction of buildings. The cost of new machinery at European market is assumed as the high-cost scenario for the cost of heavy machinery and dismantling equipment whereas the cost of used equipment is used for the low-cost scenario. The construction of pavements, roads, impermeable floors, gullies, and other infrastructure on a yard needs cement, concrete aggregate and water as raw materials. Their prices vary from country to country. Similarly, the construction costs of the building also vary. Therefore, the high and low-cost scenarios for the cost of yard infrastructure and structures are considered to analyse the changes in the costs of concrete and construction of buildings.

a) Scenario 1: upgrading an existing pier-breaking facility

The baseline facility in scenario 1 is assumed to be an existing pier-breaking facility that already has access to a sufficient number of quays and cranes to handle the dismantling of 100,000 LDT per year. The access to a floating dock facility or a slipway is also assumed to be available. The paved areas in the yard need a limited upgrade. Training programs for staff are also in place. However, one additional crane and a number of other pieces of heavy machinery are needed to allow for simultaneous dismantling of three vessels. Additionally, construction of buildings and pavement for storage and hazardous material handling areas is also required. A two-day brush-up program is anticipated for capacity building of leading staff and training courses for labourer staff.

With these assumptions, the cost analysis carried out by Overgaard et al. (2013) shows that a total investment of 9.5 million USD is required to upgrade the defined existing pier-breaking facility to a HKC-compliant facility. A total of 31% of the investment is required for heavy machinery and dismantling equipment, and 58% is required for yard infrastructure and structures. The low and high cost boundaries of investment are estimated as 6.3 million USD and 12.1 million USD, respectively. The investment cost estimate for low, baseline, and high cost boundaries of smaller dismantling capacity yards (50,000 and 25,000 LDT/year) is carried out on the basis of use of concrete and heavy machinery proportional to the dismantling capacity. The estimated investment required for three different yard sizes at three different cost scenarios is provided by Table 6.8.

Table 6.8: Estimated cost of investment to upgrade an existing pier-breaking facility to a HKC-compliant facility for different yard sizes and cost scenarios (Source: Overgaard et al. (2013))

	100,000 LDT/year	50,000 LDT/year	25,000 LDT/year
High-cost scenario	$12,100,000	$5,200,000	$2,600,000
Baseline	$9,500,000	$3,900,000	$1,900,000
Low-cost scenario	$6,300,000	$2,600,000	$1,400,000

b) Scenario 1a: upgrading a basic pier

An established pier which has not been used for recycling of ships previously is assumed as the baseline facility for scenario 1a. The site is analysed for an upgrading to a labour-intensive, less mechanized, HKC-compliant pier-breaking facility. It requires a full upgrade because no previous recycling operation is assumed and not much infrastructure is in place. Therefore, a large amount of investment is anticipated to be required. It is expected that the training and capacity building of all leading staff and labourers need five-day courses, which needs more investment than scenario 1.

With these assumptions, the cost analysis carried out by Overgaard et al. (2013) shows that an investment of 23.9 million USD is required to upgrade the defined existing basic pier to a 100,000 LDT/year HKC-compliant facility. Out of the total investment, about 35% is required for installing heavy machinery for dismantling activities, while about 51% is needed to improve the yard infrastructure. The low and high cost boundaries of investment are estimated as 16.2 million USD and 29.5 million USD, respectively. Similar to other scenarios, the investment cost estimate for low, baseline, and high cost boundaries of smaller dismantling capacity yards is carried out on the basis of use of concrete and heavy machinery proportional to the dismantling capacity. The estimated investment required for three different yard sizes at three different cost scenarios is provided by Table 6.9.

Table 6.9: Estimated cost of investment to upgrade a basic pier to a HKC-compliant facility for different yard sizes and cost scenarios (Source: Overgaard et al. (2013))

	100,000 LDT/year	50,000 LDT/year	25,000 LDT/year
High-cost scenario	$29,500,000	$17,300,000	$11,000,000
Baseline	$23,900,000	$14,300,000	$9,500,000
Low-cost scenario	$16,200,000	$9,300,000	$5,700,000

c) <u>Scenario 2: upgrading an existing slipway</u>

The baseline facility in scenario 2 is assumed to be an existing slipway facility that has no quays and dismantles one vessel at a time from the bow. No areas, except the slipway, are paved in the baseline facility. The facility should be able to dismantle two to three vessels simultaneously to achieve the capacity of 100,000 LDT per year. Therefore, two additional cranes and other pieces of heavy machinery are required to be installed. Use of barges and pontoons for operating cranes to carry out topside dismantling of one or two berthed vessels is also foreseen. A third vessel in a more advanced stage of dismantling can be pulled up a slipway. It is anticipated that all leading staff and labourers need five-day courses for training and capacity building.

With these assumptions, the cost analysis carried out by Overgaard et al. (2013) shows that an investment of 21 million USD is required to upgrade the defined existing slipway facility to a HKC-compliant facility. Out of which, about 35% is required for installing heavy machinery for dismantling activities, while about 58% is needed to improve the yard infrastructure. The low and high cost boundaries of investment are estimated as 13.6 million USD and 26.5 million USD, respectively. In this scenario as well, the investment cost estimate for low, baseline, and high cost boundaries of smaller dismantling capacity yards is carried out on the basis of use of concrete and heavy machinery proportional to the dismantling capacity. The estimated investment required for three different yard sizes at three different cost scenarios is provided by Table 6.10.

Table 6.10: Estimated cost of investment to upgrade an existing slipway facility to a HKC-compliant facility for different yard sizes and cost scenarios (Source: Overgaard et al. (2013))

	100,000 LDT/year	50,000 LDT/year	25,000 LDT/year
High-cost scenario	$26,500,000	$15,600,000	$8,900,000
Baseline	$21,000,000	$12,900,000	$7,500,000
Low-cost scenario	$13,600,000	$8,000,000	$4,300,000

d) Scenario 2a: upgrading a basic harbour

A harbour area with limited pier access is assumed as the baseline facility for scenario 2a. Similar to scenario 1a, this also needs a full upgrade and is assumed to be upgraded to a labour-intensive, less mechanized HKC-compliant slipway facility. Therefore, a large amount of investment is anticipated to be required. In this scenario, an extra amount of investment is needed to upgrade than scenario 1a because a new slipway needs to be constructed.

With these assumptions, the cost analysis carried out by Overgaard et al. (2013) shows that an investment of 24.9 million USD is required to upgrade the defined existing basic harbour to a 100,000 LDT/year HKC-compliant facility. Similar to scenario 1a, about 35% of the total investment is required for installing heavy machinery for dismantling activities, while about 51% of the total investment is needed to improve the yard infrastructure and structures. The low and high cost boundaries of investment are estimated as 17.2 million USD and 30.4 million USD, respectively. In this scenario also, the investment cost estimate for low, baseline, and high cost boundaries of smaller dismantling capacity yards is carried out on the basis of use of concrete and heavy machinery proportional to the dismantling capacity. The estimated investment required for three different yard sizes at three different cost scenarios is provided by Table 6.11.

Table 6.11: Estimated cost of investment to upgrade a basic harbour to a HKC-compliant facility for different yard sizes and cost scenarios (Source: Overgaard et al. (2013))

	100,000 LDT/year	50,000 LDT/year	25,000 LDT/year
High-cost scenario	$30,400,000	$17,600,000	$11,100,000
Baseline	$24,900,000	$14,800,000	$9,700,000
Low-cost scenario	$17,200,000	$9,800,000	$5,900,000

6.2.3 Results and discussion

6.2.3.1 Scenario 1: existing pier-breaking facility

The results provided in Figure 6.7 and Table 6.12 show that the reduction in offer price due to upgrading an existing pier-breaking facility is less than $10 per LDT for all three annual recycling capacities under all three cost scenarios. The reason for such a low reduction in offer price is mainly the low amount of investment required to upgrade an existing pier-breaking facility.

When comparing the results of different capacity yards, there is hardly any difference between the reduction in offer price by 25,000 LDT/year and 50,000 LDT/year for all three cost scenarios. In fact, the reduction is exactly same for both the yards in the high-cost scenario, i.e., $8.35 per LDT. Similarly, the difference between the results of 100,000 LDT/year capacity yards and 50,000 LDT/year capacity yards is less than two dollars per lightweight ton for high and baseline cost scenarios and less than a dollar per lightweight ton for the low-cost scenario.

The highest reduction in offer price is calculated for the 100,000 LDT/year capacity yard at the high-cost scenario ($9.71 per LDT), whereas the lowest reduction is calculated for the 50,000 LDT/year capacity yard at the low-cost scenario ($4.17 per LDT).

Table 6.12: Reduction in offer price due to the upgrade of an existing pier-braking facility to a HKC-complied yard for various annual recycling capacities and upgrade-cost scenarios

	Recycling capacity					
	100,000 LDT/year		50,000 LDT/year		25,000 LDT/year	
Cost scenario	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT
High	$12,100,000	$9.71	$5,200,000	$8.35	$2,600,000	$8.35
Baseline	$9,500,000	$7.62	$3,900,000	$6.26	$1,900,000	$6.10
Low	$6,300,000	$5.06	$2,600,000	$4.17	$1,400,000	$4.49

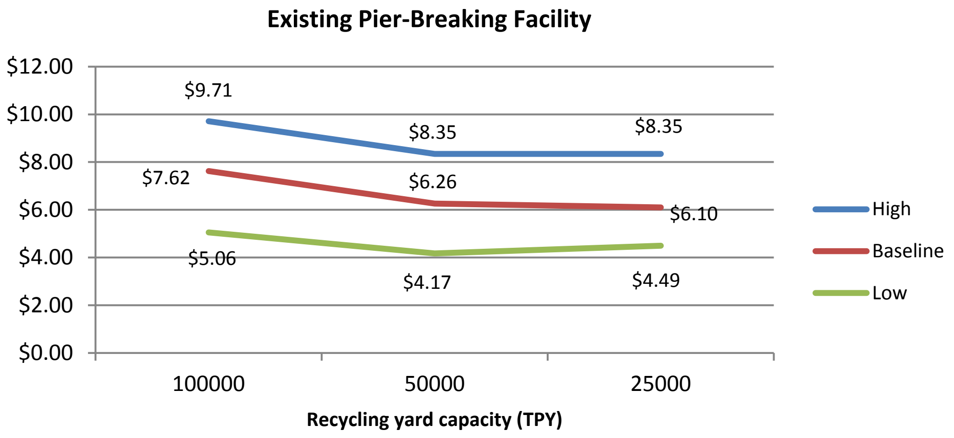


Figure 6.7: Reduction in offer price due to the upgrade of an existing pier-breaking facility to a HKC-complied yard for three different annual recycling capacities and upgrade-cost scenarios each

6.2.3.2 Scenario 1a: basic pier

The results show that upgrading a basic pier to a HKC-complied pier-breaking facility will reduce the offer price in the range of $13–$35 per LDT for different annual recycling capacities in different cost scenarios. Interestingly, unlike scenario 1, the results show that the reduction in offer price is inversely proportional to the capacity of the yard. This means that the facilities of smaller capacities are likely to reduce the offer price more than the larger capacity yards. This inference is from the fact that the change in offer price calculated for a 25,000 LDT/year capacity yard is $30.49 per LDT against $19.18 per LDT for a 100,000 LDT/year capacity yard in the baseline cost scenario.

The highest reduction in offer price is calculated for the 25,000 LDT/year capacity yard for the high-cost scenario ($35.31 per LDT), whereas the lowest reduction is calculated for the 100,000 LDT/year capacity yard for the low-cost scenario ($13 per LDT). The reduction in offer price for all three capacities of the yard at all three cost scenarios is shown in Figure 6.8 and Table 6.13.

In this scenario, a basic pier is considered for the analysis, which means that the recycling facility is non-existing. Therefore, there is no base price from which the reduction will take place. The price offered by an existing non-compliant pier-breaking facility is assumed for that purpose. For example, an existing non-compliant pier-breaking facility of 100,000 LDT/year capacity offers $100 per LDT; in a baseline cost scenario, upgradation to a compliant facility will reduce the offer price by $7.62 per LDT (Table 6.12), whereas the upgradation of a basic pier will reduce the price by $19.18 per LDT (Table 6.13).

Table 6.13: Reduction in offer price due to the upgrade of a basic pier to a HKC-complied yard for various annual recycling capacities and upgrade-cost scenarios

	Recycling capacity					
	100,000 LDT/year		50,000 LDT/year		25,000 LDT/year	
Cost scenario	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT
High	$29,500,000	$23.67	$17,300,000	$27.76	$11,000,000	$35.31
Baseline	$23,900,000	$19.18	$14,300,000	$22.95	$9,500,000	$30.49
Low	$16,200,000	$13.00	$9,300,000	$14.93	$5,700,000	$18.30

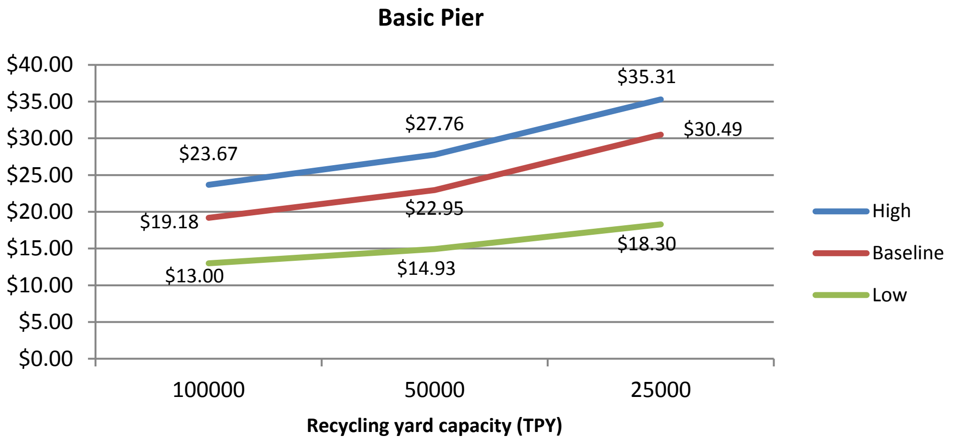


Figure 6.8: Reduction in offer price due to the upgrade of a basic pier to a HKC-complied yard for three different annual recycling capacities and upgrade-cost scenarios each

6.2.3.3 Scenario 2: existing slipway facility

The results show that the reduction in offer price due the upgrade of an existing slipway facility is in the range of $10–$28 per LDT for different annual recycling capacities under different cost scenarios. When comparing the results of yards having different annual recycling capacities, it is clear that lower the recycling capacity, higher the change in offer price. For instance, in a baseline cost scenario, the change in offer price for a yard with 25,000 LDT/year capacity ($24.07 per LDT) is higher than the change in offer price for both the yards with 50,000 LDT/year capacity ($20.70 per LDT) and 100,000 LDT/year capacity ($16.85 per LDT). Similar results can be seen for the other two cost scenarios.

The highest reduction in offer price is calculated for the yard having a 25,000 LDT/year capacity at the high-cost scenario ($28.57 per LDT), whereas the lowest reduction is calculated for the yard having a 100,000 LDT/year capacity at the low-cost scenario ($10.91 per LDT). The reduction in offer price for all three capacities of the yard at all three cost scenarios is shown in Figure 6.9 and Table 6.14.

The comparison of scenarios 1 and 2 finds that the change in offer price for an existing slipway yard is approximately two, three and four times the change in offer price for an existing pier facility of 100,000 LDT/year, 50,000 LDT/year and 25,000 LDT/year capacity, respectively. This is mainly due to the comparatively high fixed cost of upgrading an existing slipway facility and the relatively less number of variable elements within the costs.

Table 6.14: Reduction in offer price due to the upgrade of an existing slipway facility to a HKC-complied yard for various annual recycling capacities and upgrade-cost scenarios

	Recycling capacity					
	100,000 LDT/year		**50,000 LDT/year**		**25,000 LDT/year**	
Cost scenario	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT
High	$26,500,000	$21.26	$15,600,000	$25.04	$8,900,000	$28.57
Baseline	$21,000,000	$16.85	$12,900,000	$20.70	$7,500,000	$24.07
Low	$13,600,000	$10.91	$8,000,000	$12.84	$4,300,000	$13.80

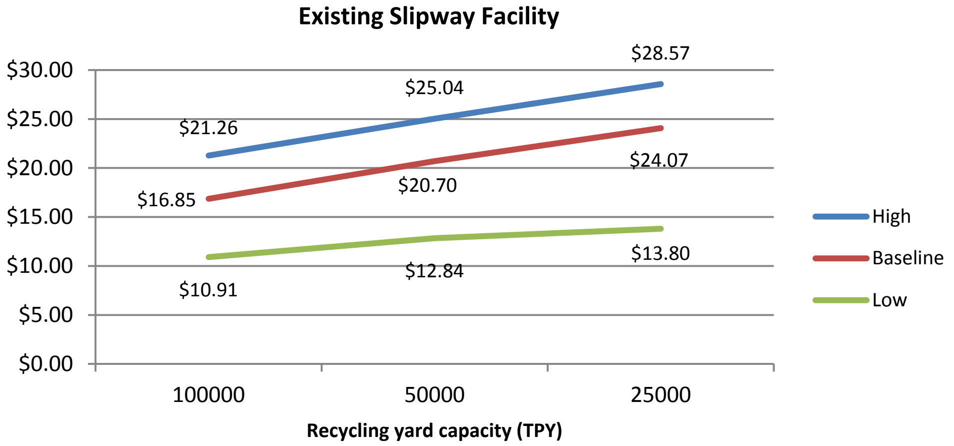


Figure 6.9: Reduction in offer price due to the upgrade of an existing slipway facility to a HKC-complied yard for three different annual recycling capacities and upgrade-cost scenarios each

6.2.3.4 Scenario 2a: basic harbor

In this scenario, a basic harbour is considered for the analysis, which means that the recycling facility is non-existing. Therefore, similar to scenario 1a, there is no base price from which the reduction will take place. The price offered by an existing non-compliant slipway facility is assumed for that purpose because the cost of upgrade to a compliant slipway facility is considered for analysis (as explained in section 6.2.2.4 (d)). For example, an existing non-compliant slipway facility of 100,000 LDT/year capacities offers $100 per LDT; in a baseline cost scenario, upgrading to a compliant facility will reduce the offer price by $16.85 per LDT (Table 6.14), whereas upgrading a basic harbour will reduce the price by $19.98 per LDT (Table 6.15).

The results show that upgrading a basic harbour to a HKC-complied slipway facility will reduce the offer price in the range of $13–$35 per LDT for different annual recycling capacities in different cost scenarios. Similar to scenarios 1a and 2, the results show that the reduction in offer price is inversely proportional to the capacity of the yard. This means that the facilities of smaller capacities are likely to reduce the offer price more than the larger capacity yards. This inference is from the fact that the change in offer price calculated for a 25,000 LDT/year capacity yard is $31.13 per LDT against $19.98 per LDT for a 100,000 LDT/year capacity yard in the baseline cost scenario.

Similar to scenario 1a, the highest reduction in offer price is calculated for the yard having an annual recycling capacity of 25,000 LDT at the high-cost scenario ($35.63 per LDT), whereas the lowest reduction is calculated for the yard having an annual recycling capacity of 100,000 LDT at the low-cost scenario ($13.80 per LDT). The reduction in offer price for all three capacities of the yard at all three cost scenarios is shown in Figure 6.10 and Table 6.15.

Table 6.15: Reduction in offer price due to the upgrade of a basic harbour to a HKC-complied yard for various annual recycling capacities and upgrade-cost scenarios

	Recycling capacity					
	100,000 LDT/year		**50,000 LDT/year**		**25,000 LDT/year**	
Cost scenario	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT	Upgradation cost	Reduction in price $/LDT
High	$30,400,000	$24.39	$17,600,000	$28.25	$11,100,000	$35.63
Baseline	$24,900,000	$19.98	$14,800,000	$23.75	$9,700,000	$31.13
Low	$17,200,000	$13.80	$9,800,000	$15.73	$5,900,000	$18.94

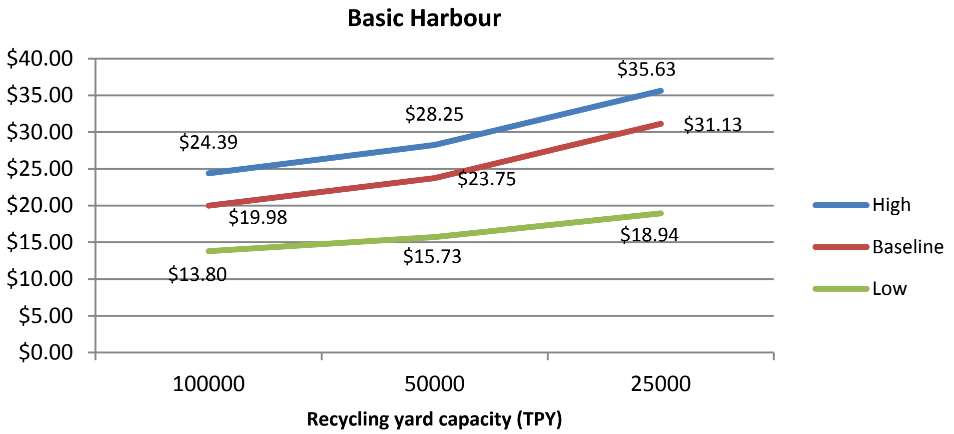


Figure 6.10: Reduction in offer price due to the upgrade of a basic harbour to a HKC-complied yard for three different annual recycling capacities and upgrade-cost scenarios each

6.2.4 Conclusions

This case study explained a re-engineered NPV model that can estimate the reduction in offer price as a result of investments made to upgrade a non-compliant ship recycling facility to a HKC-compliant facility. The impact of upgrading a basic pier and an existing pier-breaking recycling facility to a HKC-compliant pier-breaking facility and the impact of upgrading a basic harbour and an existing slipway recycling facility to a HKC-compliant slipway facility is studied.

The results show that upgrading an existing pier-breaking facility is not likely to bring a very huge reduction in the offer price. It is likely to be in the range of $4 to $9 per LDT. On the contrary, upgrading other types of facilities is likely to reduce the offer price in the range on $10 to $35 per LDT depending on the initial facility type, recycling capacity and the upgrade cost scenario. Despite several parameters affecting the reduction in offer price, it can be clearly concluded from the results that the recycling facilities of low capacity are likely to reduce the offer price more than the facilities of large capacity. Only exception to this is upgrading an existing pier-breaking facility, for which the reduction in offer price is estimated to be similar for all three recycling capacities analysed.

Concisely, the results show that there will not be a huge reduction in offer price as a result of upgrading non-compliant pier-breaking recycling yards whereas upgrading non-compliant slipway facilities will result in a large reduction in offer price. At the same time, upgrading a harbour to either a pier-breaking facility (scenario 1a) or a slipway facility (scenario 2a) will not have much difference in terms of amount of reduction in the offer price. This is obviously due to the similar amount of upgrading costs required for both the scenarios.

The implementation of the HKC might improve the health, safety and environmental standards of the ship recycling yards. However, resulting reduction in offer price will discourage ship owners to recycle obsolete ships in the newly improved yards, especially if they are able to get a better price for the same ship in a non-compliant yard. This will be detrimental for the contribution of the ship recycling industry towards sustainability. Therefore, there is a need to find certain effective ways that can improve the profitability of a HKC-compliant ship recycling yard so that it can offer at least equal, if not more than the price offered by a non-compliant yard to buy an EOL ship.

6.3 Summary and concluding remarks

This chapter discussed two important economic aspects of the ship recycling yards. First, how can ship recycling yards turn waste into resources and eventually earn revenue from them; and second, what is the impact of the HKC on the price offered by newly complied yards to buy end-of-life ships. An economic assessment model is developed and applied to evaluate the change in offer price due to both the conditions.

The increase in offer price due to waste-to-energy technology (plasma gasification) is not likely to be substantial, yet the ship recycling process can be made cleaner due to it. This might attract certain socially responsible ship owners to recycle their ships on a yard fitted with a plasma technology. After all, following the principles of corporate social responsibility is likely to boost the reputation of a company.

The reduction in offer price due to the Hong Kong convention depends on the costs required to upgrade a recycling facility. The analyses carried out for different types of facilities concludes that the offer price can be reduced up to $35 per LDT due to very high HKC compliance costs for certain facility types.

The results of the two case analyses imply that it is highly unlikely for newly compliant yards to offer the similar price as they were offering when they were not HKC compliant even after using advance waste-to-energy technology such as plasma gasification. It is because of the fact that the reduction in offer price due to

HKC is much larger than the increase in offer price due to plasma gasification. Therefore, it can be concluded that waste-to-energy technology will not be able to close the gap between the prices offered by compliant and non-compliant yards. However, the gap can be filled-in partially.

CHAPTER 7

DESIGN FOR RECYCLING[‡‡]

“Truth suffers from too much analysis.”

\- Frank Herbert (1920-1986), Novelist

[‡‡] This chapter is partially based on the peer-reviewed conference papers presented at MARTECH 2014 (Jain et al., 2014) and MARTECH 2016 (Jain et al., 2016a). The section 7.6 (case study 2) is purely based on Jain et al. (2016a), while other parts of the chapter are reproduced by combining both these conference papers and new unpublished research.

Chapter 3 argued that an improved ship design can facilitate safe and environmentally sound ship recycling. Ideally, a ship must be designed to ensure that the ship's structure is easy to dismantle and the ship related information is easily available at the end of ship's life. The ship design process is primarily influenced by operational requirements stipulated by the ship owner, safety requirements stipulated by international regulations such as MARPOL, SOLAS, IMO codes, and production requirements specified by the shipyard. Unfortunately, the final phase of a ship's lifecycle, i.e. recycling, is usually not part of this process mainly because of lack co-ordination between various stakeholders involved in different stages of a ship's lifecycle. These include ship owners, ship designers, shipyards, classification societies, ship recycling yards and regulatory authorities.

This chapter discusses how the information about ship's materials can be stored in ship documents as early as during the design stage. Presently, this might be obtained from the lightweight distribution given in the ship's stability manual, as discussed in Chapter 4. Unfortunately, it is neither standardized nor extensive enough. Therefore, this chapter proposes a new format of lightweight distribution in order to store such critical information for ship recyclers. The proposed format is meant to assist the ship recycling process currently employed by green recycling yard, i.e., ship's lightweight is distributed up to the materials level only to some extent. However, the format should further be updated if in future ship's lightweight is fully required to be distributed up to the materials level. This chapter also presents the improvements to the design of a bulk carrier pertaining to the needs and requirements of the ship recycling yards.

7.1 Introduction

Ship design and engineering is an interesting field of study. There are many stakeholders with an interest and a say in the design of a vessel. This includes ship owner, ship designers, shipyard, classification society, suppliers of materials and equipment, national and international maritime organizations, ship brokers, technical consultants and ship's crew (Rogne, 1974, Solesvik, 2007). The ship owner has a large influence in selecting a yard and defining the main design specifications, such as vessel size and speed. The main variable for the ship owner to buy a ship is its earnings potential which is influenced by these design specifications (Veenstra and Ludema, 2006). The ship owner may decide either to order (1) a sister vessel of an existing design, or (2) a similar design with minor changes, or (3) a new design, or (4) a new and innovative ship having a fundamentally novel design (Solesvik, 2007, Veenstra and Ludema, 2006). In most cases, however, ship owners, ship brokers and shipyards prefer to build ships from existing designs (Buxton, 1976).

In both cases, existing and new designs, the shipyard usually does the engineering and is thus able to influence the building costs of the vessel to a large extent. Most shipyards have their own in-house naval architect companies or departments so that time efficiency for coordination and price reduction can be achieved as the naval architects are aware of shipyard's production facilities, technical standards and features (Solesvik, 2007). The interests of the crew lies in their wellbeing and safety protected by international regulations such as MARPOL, SOLAS, and IMO codes. These regulations also govern the safe and environmentally sound operation of the ship, which is of interest to charterers, ship owners and operators. In essence, ships are designed keeping in mind only the production and operation phase of their lifecycle.

Concisely, in the beginning, ships were designed to meet just the design criteria and choices were made based on production costs but with time, ship design has moved from considering only design parameters to consider operational requirements as well. This statement is supported by various authors, for e.g., Bertram and Thiart (2005), Papanikolaou et al. (2009), Nowacki (2010), Gaspar et al. (2012) and van Bruinessen et al. (2013) to name a few. Unfortunately, the final phase of ship's lifecycle i.e. recycling is taken into account neither by the ship owners nor by the ship designers. This is despite the fact that health, safety and environmental problems associated with the ship recycling industry have been in focus for nearly two decades since Brazilian photographer Sebastiao Salgado's Pulitzer prize winning book 'Workers' showing the pictures of labourers working on ship breaking beaches in Bangladesh was published in 1993.

The lifespan of a ship comprises of four phases; design, construction, operation and recycling. The first three phases of ship's life cycle are closely related to each other while the last stage i.e. recycling has no interaction with other three phases. The argument of this chapter is that the last leg of the life cycle of the ship should also be taken into account during ship design considering the fact that ships will have to be demolished at the end of their economic lives. This chapter emphasizes the need to take a holistic view in order to effectively deal with the health, safety and environmental concerns related to ship recycling. Materials acquired by a ship during its lifetime in design, construction, operation and maintenance phase remains with it till its very end when it reaches ship recycling yard for demolition. The condition of an end of life ship along with its structural complexity and material streams governs the health, safety and environmental threats it poses while being recycled. Thus, there is urgent need to create a link between the first and last stage of the life cycle of the ship so that a feedback can be given to ship design stage.

In order to facilitate safe and environmentally sound ship recycling, besides improving the standards of recycling facilities it is imperative to design ships that are environmentally friendly, safe and easy to recycle. The concept of 'design-for-recycling' must be implemented to facilitate improvements in ship designs. As discussed in Chapter 3, it is a fairly new concept which is well developed for end-of-life vehicles but not for end-of-life ships. This chapter aims to review the concept with respect to ships and recommend the future course of designing ships in such a way that ships can be recycled without imposing hazards to the environment and to the health and safety of the humans involved in the process of ship recycling.

7.2 Literature review

The issue of ship recycling has been on the agenda of several parties including NGOs, government agencies, and international organizations such as International Maritime Organization (IMO) and International Labour Organization (ILO). In fact, several reports highlighting the concerns related to environment and precarious condition of workers in ship recycling facilities have been published by NGOs such as Greenpeace and NGO Shipbreaking platform (Iqbal and Heidegger, 2013, Sarraf, 2010, UNESCO, 2004, Vardar et al., 2005).

In the past decade, several researchers have focused their studies around the area of ship design in order to establish safe and environmentally sound ship recycling methods. The concept has also been on the industry agenda since long, mainly in the form of guidelines, code of practices and unenforced regulations such as EU ship recycling regulation and IMO Hong Kong convention (EU, 2013, IMO, 2003, IMO, 2009, Marisec, 2001).

Based on the best practices of the automobile recycling, the research carried out by McKenna et al. (2012) stressed upon the need to incorporate the design-for-recycling principles into marine design. They identified certain problem areas of ship recycling that are likely to have a solution within the ship design phase. Sivaprasad and Nandakumar (2013) proposed a new model for ship lifecycle by adding a few more stages to the traditional ship lifecycle to implement the concept of design-for-recycling. Alkaner et al. (2006) compared the ship recycling process with ship production to identify key performance indicators of both the processes. They stressed upon the need to apply various "design for" concepts such as design-for-environment and design-for-dismantling in marine technology field. They also emphasized to consider material inventory and reusability issues of end-of-life ships as early as possible during the design stage of the ship.

7.3 Problem description and methodology

Most academic studies focused on changes to the traditional marine design cycle. These studies concluded that designing a ship meeting the requirements of the last stage of the ship's lifecycle (recycling) would be beneficial in raising the standards of the ship recycling industry, eventually leading to safe and environmentally sound ship recycling. On the other hand, the industry focused on developing policies and guidelines to stimulate the use of design-for-recycling concept within the ship design and to regulate and improve the recycling yards. However, such efforts carried out by the academic researchers and the industry have failed to demonstrate exactly how the concept of design-for-recycling can assist in achieving cost-effective green ship recycling.

Therefore, this chapter proposes to study the current ship recycling process scientifically envisaging two fold benefits. Firstly, a feedback from recycling phase to design phase can be provided to correct anomalies in future ship designs so that ship recycling can be carried out without imposing HSE concerns. Secondly, optimization of the ship recycling process can be done taking into account international regulations such as Hong Kong convention and EU ship recycling regulation to reduce costs incurred in green ship recycling services. The analysis of the ship recycling process carried out in Chapters 4 and 5 resulted in concluding that it is important for both the ship owners and the ship recyclers to know exactly what will be recycled, i.e., all the materials (not just hazardous) on board a ship at the end of its life.

The known quantities of materials present on board will improve the calculation of costs and income as well as the planning of the recycling process. For example, knowing the quantity of steel, non-ferrous metal and other scraps in an end-of-life ship can help estimate the scrap value of the ship, using which ship owners can negotiate the selling price with ship recyclers while ship recycling yards can estimate the earning potential of recycling that ship. Moreover, quantification of all the materials helps in dealing with a situation where the material which is considered non-hazardous today is classified as hazardous in the future. For instance, asbestos, PCB and halons were not considered hazardous for many years.

The recycling yards now rely on experience and guess work to determine the quantity of materials available on an end-of-life ship. However, it is already discussed in Chapter 4 that valuable suitable information might be obtained from the lightweight distribution given in the stability manual of the ship. This information is, however, neither standardized nor quite extensive enough. The Chapter 4 also discussed that the lightweight distribution of the case ship contains a lot of ambiguous information which lacks details needed by a recycling yard to develop the ship recycling plan. The format of the lightweight distribution of ships differs from ship to ship depending on the procedures employed by the shipyard making it even impractical for recycling yards, in certain cases, to use the lightweight distribution which is not detailed enough.

Therefore, this chapter focuses on the potential of storing the minimal required information about ship's materials as early as during its design stage within the proposed format of the lightweight distribution. To some extent, this format helps in obtaining material wise breakdown of ship's lightweight instead of existing component wise classification. It can provide valuable information to shipyard, classification society, ship's crew and ship owner during the lifetime of the vessel and to ship recycling yard and ship owner at the end of ship's life, if standardized by regulations. This chapter continues the work done in Chapter 4 to further analyse the lightweight distribution of the case ship to develop a format that can be used by shipyards to store the valuable information required by the ship recycling yards at the end of ship's life.

Besides proposing a new format of the lightweight distribution of the ship, this chapter also proposes the structural changes to an 11,000 T lightweight handymax bulk carrier built in 2006, which is studied as a case ship for the purpose of this research. The reason for choosing a bulk carrier for such analysis is based on the fact that every year since 2011 bulk carriers represent more than a third of the total lightweight of the ships recycled. In fact, bulk carriers represent 35% of the total lightweight of the ships recycled in last four years, followed by 19% represented by general cargo ships, 18% represented by tankers and 15% represented by container ships (Bois, 2012, Bois, 2013, Bois, 2014, Bois, 2015). Moreover, the stability manual of this particular ship is available in the public domain (CarlBro, 2006).

In conclusion, this chapter aims to answer research questions such as, (1) how to analyse and recommend changes to the ship's lightweight distribution, and (2) what structural changes can be made to a ship to improve ship recycling and what is the impact of such changes during the various stages of the ship's lifecycle. Therefore, this chapter continues with the description of the concept of design-for-recycling with reference to ships and investigates the areas in ship design that may be improved with the aim of alleviating the hazards related to ship recycling. A list of recommendations is developed based on the literature and some of them are applied on the case ship to understand the costs and benefits during the ship's lifecycle. Besides applying a few of the recommended structural changes to the case ship, a methodology is proposed and implemented to analyse and update the lightweight distribution of the case ship in such a way that it can be useful during ship recycling.

7.4 Design-for-recycling concept

Ships are not usually designed keeping in mind the needs and demands of the end customer i.e. the ship recycling yards. The operational and functional requirements of ship owner and regulatory concerns are of paramount importance during the design and production phase of the ships (Lamb, 2003). It can be argued that the interests of end customer must be taken into account during the preliminary phase of life cycle of the ship so that materials that can be a threat to workers' health or the local environment during dismantling are not used in ship construction. The major advantage of design-for-recycling concept is that it reduces risk throughout the ship's life (LR, 2011). A carefully designed ship having fewer probabilities of hazards to take place is definitely a safer ship for builders, crew, visitors, passengers, buyers and recyclers.

The basic principle of design-for-recycling concept is to design the ship in such a way that the recycling process becomes as safe, efficient and environmentally sound as possible once ship reaches the end of its life. According to IMO guidelines (IMO, 2003), design for ship recycling is a set of design tips which include proper design/selection of structural parts, equipment, material and knowledge base that will facilitate clean and safe partial/ full dismantling of ships, maximum use of recycled products/parts in ship production, and reduction in number of inseparable components/parts in on board equipment assemblies. This definition has been slightly modified by Sivaprasad et al. (2012) keeping in mind entire life cycle of the ship from design to construction, operation and recycling. According to the modified definition, design for ship recycling is a set of design and development activities spread over the entire life cycle stages of a ship, incorporating ideas for design/selection of structural parts, equipment, material and knowledge base that will facilitate clean and safe partial or end of life recycling of a ship and its components.

In order to apply this concept it is imperative to identify the problem areas within ship recycling which must be given extra attention during the design stage of a ship. Major areas of concern within ship recycling industry causing health and environmental impacts include the use of hazardous materials such as asbestos and PCBs within the design and construction of a vessel; toxicity of paints and coatings used on ships and the complexity in design and layout of overall ship structure, especially machinery compartment and oil tanks which have to be manually cleaned before subjected to cutting operation.

The concept of design-for-recycling also requires documenting all the hazardous materials used in ship construction so that a relevant plan can be made to recycle the ship based on this inventory of hazardous materials (LR, 2011). There are over 65 hazardous or potentially hazardous items which are required to be documented by the Hong Kong convention on ship recycling (IMO, 2009). Unfortunately, this convention is not yet in force.

The design-for-recycling concept is aimed at maximizing the value of an end of life ship by minimizing the recycling costs. In a nutshell, three key objectives of design for ship recycling concept are (LR, 2011):

1. To reduce or replace hazardous materials.
2. To accurately provide an inventory of hazardous materials.
3. To make the ship easy to dismantle.

7.4.1 Reduce or replace hazardous materials

Material stream as a result of end of life ship recycling process may contain many hazardous materials such as asbestos, polychlorinated biphenyls (PCBs), ozone depleting substances (ODS), radioactive substances, anti-fouling compounds, heavy metals, residual oil (fuel/lube/hydraulic), chemicals etc. The massive nature and complexity of ships along with use of such hazardous materials for ship building is a potential threat to green ship recycling. It is thus required to minimize the use of hazardous materials in ship building. IMOs Hong Kong convention on ship recycling also restricts and prohibits the use of hazardous materials on ships during design, construction, operation and repair phase of ship's life cycle.

Whether it is asbestos used for insulation, heavy metals used in paints or residual oil in various ship systems; they affect humans and environment during ship recycling and can be dealt with during design stage. They should be replaced with other suitable non-hazardous alternatives to attain safe and environmentally sound ship recycling. Replacing hazardous materials depends on finding suitable alternatives having desired properties. Thus, it is required to carry out research in this field to find out suitable alternatives for hazardous materials used in ship design and construction. There are opportunities to find suitable replacements of hazardous materials used on ships taking relevant analogies from other industries such as automobile, aviation, offshore, housing etc.

While some of the elements such as fuel oil, lube oil etc. cannot be replaced; some research has been carried out to replace certain hazardous materials such as asbestos, tri-butyl-tin (TBT) in antifouling paints, and chloro-fluoro-carbons (CFCs) in refrigerants after they were banned by IMO regulations (ABS, 2011). Today, a number of effective anti-fouling systems are available which do not contain TBT. These include organotin-free anti-fouling paints, and biocide-free non-stick coatings that have an extremely slippery surface to prevent fouling from occurring, and which make surfaces easier to clean when fouling occurs (Xu et al., 2012).

Although, banned substances are not used in new ships, they were used in old ships because of their superior performance. Asbestos, for example, not only has fire retardant and insulating characteristics, but also has additional strength due to the nature of its fibres. It made materials stronger as well as more heat resistant (LR, 2011) but it also brought on health issues which had an incubation time of 20-30 years. These issues were thus discovered at a later stage consequently resulting in the ban of asbestos. Clearly, it is not always possible to anticipate which currently normal and widely used material might be deemed hazardous in the future. Thus preventing/foregoing/forbidding the use of currently identified hazardous materials in ships is not enough. The next section might help in securing a way out of this issue.

7.4.2 Inventory of hazardous materials

The importance of an inventory detailing the type, amount, and location of hazardous materials used in ship construction and operation is increasingly recognized as a means to enhance on board safety and environmental awareness, both throughout the ship's economic life and at the end of ship's useful life, when the ship is being prepared for recycling. The Inventory of Hazardous Materials (IHM) would be made mandatory for all ships, new and existing, when IMOs Hong Kong convention on ship recycling comes into force.

IHM enables the ship's crew and the workers at the recycling facility to take appropriate precautions against the risks of exposure to these materials. IHM is also useful in formulating a systematic plan for re-cycling a ship at the end of its useful life keeping in mind the harmful effects of hazardous materials. According to the Hong Kong convention, inventory shall be divided into three parts i.e. part 1: hazardous materials contained in the ship's structure and equipment, part 2: operationally generated waste and part 3: stores. Moreover, suppliers to the shipping industry are required to make a declaration if the materials they are supplying contain hazardous materials mentioned in the IHM and are over the specified threshold level. Thus regulation, if comes into force, would cover the entire supply chain of shipping industry, over the whole life cycle of the vessel to maintain the inventory of hazardous materials. It is far easier and more accurate to create an IHM for new builds than for existing ships (LR, 2011).

Though an IHM list for all the ships as required by IMOs Hong Kong convention is a significant step towards safe and environmentally sound ship recycling; this section emphasizes to have an inventory detailing all the materials on board, hazardous or non-hazardous. This requires cooperation of the full supply chain, including all the suppliers through the whole life cycle of the vessel. Such an exhaustive inventory of materials would create an exact picture of location of materials that are being utilized in different areas and parts of a ship. Com-piling such an exhaustive inventory is not an easy task but benefits to operators and recyclers outweigh all the efforts and investment required. Also, with advanced computer technology of today storing this information inside the ships' (3D) drawings is not a problem.

Maersk Line's idea of 'cradle to cradle passport' to create a full inventory of the materials for its new Triple-E container vessels supports the feasibility and practicality of creating such an exhaustive inventory database covering all the materials in the ship. The 'cradle to cradle passport' of Maersk is a full inventory database created to achieve total vessel recycling as it covers 95% of the weight of the ship focusing on the hull structure, engines and other significant parts of the vessels (Sterling, 2011).

7.4.3 Ease of dismantling

The value of an end of life ship, to some extent, depends on how easy or difficult it is to dismantle. There is no “easy” way to dismantle a ship but there are certain aspects of ship design and construction which, if attended properly can improve ship recycling to a great extent. The areas of ship design to be focused can be determined by applying knowledge gained due to challenges and problems faced during ship recycling. Several aspects of ship design and construction that need attention have been indicated by various authors. For example,

- Standardization of all the parts and equipment on every ship would result in a lot simpler and easier to control identification of parts and components of end of life ships for potential reuse, remanufacturing or recycling (McKenna et al., 2012).
- The concept of using modules such as toilet modules, cabin modules provide easy access for maintenance and removal whereas the use of same type of stiffeners for hull structure and reduction in variety of materials in insulation, panelling etc. within appropriate rules would make recycling a ship easier (Alkaner et al., 2006).
- Inclusion of properly designed lifting supports for handling the dismantled structural parts and on board equipment is required to minimize accidents due to falling components during ship dismantling phase. These critical items can be included in the detailed structural design stage itself (Sivaprasad and Nandakumar, 2013).
- Layout of spaces located in narrow areas of the ship such as engine room, pump room, forecastle, deck and other store rooms in the forward part of the ship should be made taking into consideration the dismantling requirements (Sivaprasad and Nandakumar, 2013).
- Designing fuel oil and other systems carrying hazardous liquids to allow for vacuum pre-cleaning could be an innovative and effective way to reduce hazards during dismantling phase of the ship (McKenna et al., 2012).
- A clear indication of where the original construction blocks were assembled together during ship construction would enable recycler to apply reverse block dismantling approach to identify elements such as access

points to hazardous materials, potential hazards and key ship recycling procedures (McKenna et al., 2012).

- Use of cap and pin method to install insulation instead of glue would make it much easier to remove insulation during ship recycling. This would negate the need of undergoing cumbersome job of scraping glue from steel structure before starting gas cutting (Rozenveld, 2010).
- Reduced height of piping installation or strategically designed location of pipes within engine room would minimize the accidents such as falling from heights during ship recycling. It would also allow an easier approach for gas cutting torches (Blankestijn, 2012).

This list is not exhaustive, but shows that most improvements are to be sought in either mitigating the risks to dismantling workers or making separation of materials easier. New areas can be identified by giving feedback from the recycling stage to the design stage. But the question is how this knowledge can be incorporated into conventional ship design process. This section proposes to use this derived knowledge as design input. According to Vassalos (2009) design input concerns performance expectations such as payload, deadweight capacity, reliability, etc.; requirements of ship owner and other stakeholders such as charterers, shipyards, etc.; and constraints posed by class requirements, SOLAS, ISM and other IMO codes. The ship owner's requirement almost always concern operational phase of ship's life cycle due to commercial reasons. Thus, most suitable way of using the derived knowledge of recycling phase as design input is to incorporate this in design rules either as class requirements or within IMO codes.

Though the need to design ships for recycling is emphasized in this section; importance of skilful operations of ships cannot be neglected. For example, heavy oil spilled into the bilges of engine room during the operational life of a ship is very difficult to clean during ship recycling. A little care taken by ship's staff to keep engine room bilges clean and oil free when ship is in service can be of great help to the workers of ship recycling industry. A stricter inspection regime by port state controls can be instrumental in achieving this objective.

7.5 Case study 1: improving ship structure

7.5.1 Research outline

The aim of this case study is to assess the applicability of few design changes to the case ship and study the consequences of design changes during each stage of the ship’s lifecycle. The design changes are selected from the ones that are short-listed as a result of the discussion on design-for-recycling concept. The selection of design changes/design features depends on two factors. First, the practicality of conducting research using the limited amount of information available; and second, the effectiveness of a design feature to support ease of dismantling. Therefore, two options, reverse production and modular accommodation are selected and analysed.

7.5.2 Reverse production

A ship is usually built by assembling together several small blocks comprising of smaller sections, often pre-fabricated and pre-outfitted with panelling, cabling, piping, etc. A logical approach to dismantle a ship’s hull would be to follow a reverse production approach, i.e., to cut it into several small blocks weighing close to the maximum lifting capacity of the crane available at the recycling yard. These small blocks can be easily handled ashore for further dismantling into sections and finally into steel plates and scrap of required dimensions.

The concept of reverse production with reference to end-of-life ships is aimed at dismantling a ship in a reverse sequence of how it was built. For this, the ship does not have to be built differently than it is done now, focussing on the strength and safety of the structure, the operational life and the cost savings during the production process. A ship must be built in such a way that the planning to divide a ship into several small blocks can be carried out easily during dismantling. The weight of each block can be calculated during the design and engineering phase of a ship’s lifecycle. This must be accurately documented so that a recycling yard can plan the efficient use of cranes in the lifting process. The information on how the ship was assembled from small blocks, weight and position of such blocks can be useful for recycling yards to plan the recycling process following the concept of reverse production. Therefore, this chapter analyses the information available in the stability manual of the case ship to assess whether the cutting operations can be planned to achieve reverse production or not. As a result, design improvements to achieve an effective and efficient reverse production are suggested.

7.5.2.1 Planning the cutting operations

The weight of the dismantling blocks may differ from recycling yard to yard depending on the maximum capacity of the crane. The accessibility for the steel cutters also limits the size of the blocks that can be cut from the ship’s hull. Additionally, the location of the machinery, piping, other equipment, and the bulkheads may also influence the weight and size of the dismantling blocks depending on the location where the blocks are separated from the ship’s hull. Ideally, the sequence of block dismantling should be the reverse building sequence. However, ship’s stability should also be considered to prevent fall of blocks and steel sections to avoid accidents and injuries to workers.

The average capacities of cranes in ship recycling yards around the world are less than the capacities of cranes in the ship building yards. Therefore, it is not possible to follow the exact reverse production process. The dismantling blocks need to be reduced to smaller sizes than they were produced. However, smaller the size of the blocks detached from the ship’s hull while the ship is in the dock or alongside the quay, longer the time occupied by the ship at the dock or the quay. This will result in slowing down the entire operations at the recycling yard. Therefore, for this case study it is assumed that the recycling yard can handle a maximum of 500 tonnes blocks during the process of primary cutting. These can be cut into smaller pieces ashore during the secondary cutting operations.

In order to plan the cutting operations, the case ship can be divided into four main sections, forepeak, cargo section, machinery section, and accommodation. The lightweight distribution of the case ship provided in its stability manual can be referred to determine the weights of the sections (Table 4.2). The ship’s stability manual also provides the general arrangement of the ship (Appendix G) and other useful information for planning the cutting operations, such as the thickness of the shell plating.

Using the information from the stability manual it is clear that the forepeak block of the case ship is 10.80 m long and has the widest upper part of 25 m. The weight of this block including the outfitting is 540T (320 + 220). Therefore, it can be dismantled as one block using a 500T crane if few forward out-fittings such as winches and anchors are removed to reduce the weight of the block from 540 T to 500T. Theoretically, entire accommodation section can be handled by one crane as it weighs 320T. However, practically it is not done so because of the heterogeneous nature of materials present in a ship’s accommodation. Generally, different types of materials are removed separately, and when the bare hull remains, accommodation section is cut into smaller pieces using gas-cutting torches. The ship’s machinery section and cargo section weigh 1070T and 5600T, respectively. Therefore, they need to be divided into smaller sections for dismantling.

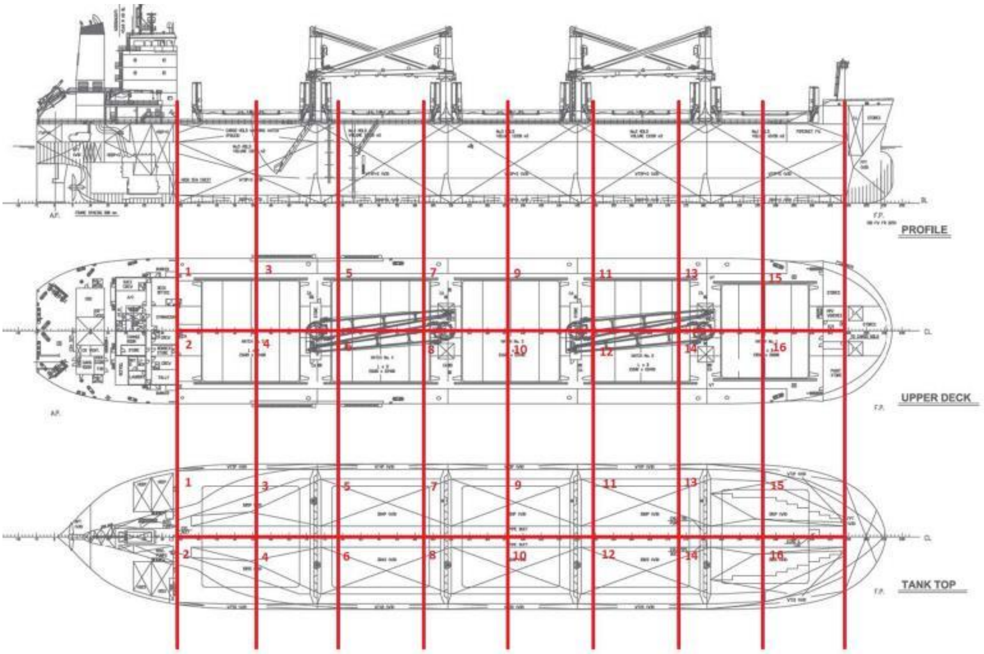


Figure 7.1: The plan of the cutting process of the case ship (Berendschot et al., 2015)

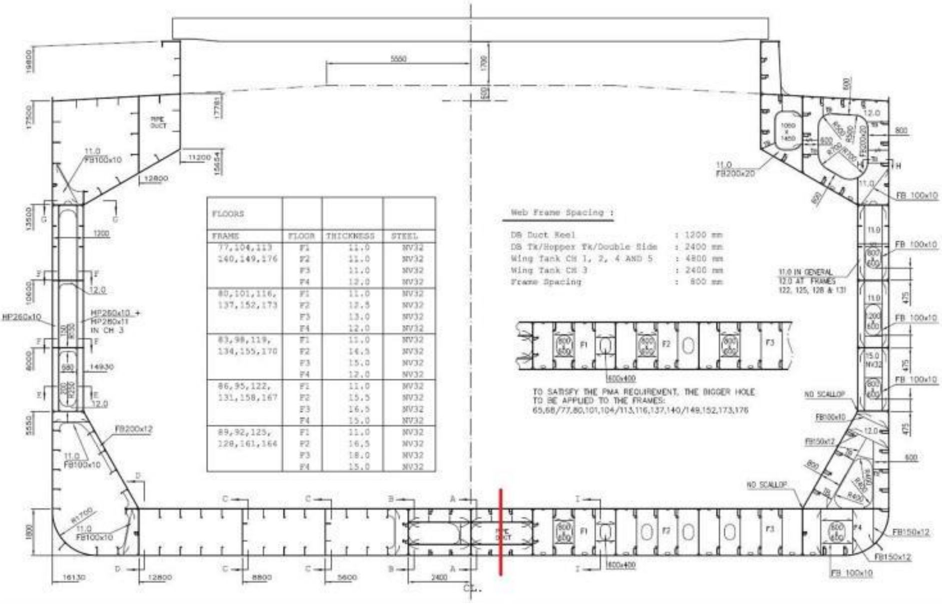


Figure 7.2: The midship section showing the planning of the cutting process of the case ship (Berendschot et al., 2015)

The total weight of the cargo section including the hatch coaming and the four transverse bulkheads separating each of the five cargo holds is 6565T (5600 + 205 + 182 + 198 + 198 + 182). The easiest and most straight forward way of breaking down the ship's cargo section would be to divide it into five blocks weighing 1313T each. However, these blocks will be too heavy to be handled by the assumed cranes available at the ship recycling yard. Therefore, the case ship must be planned to be cut into smaller blocks. Cutting the double bottom and transverse bulkheads longitudinally and the cargo holds transversely with an intermediate distance of 18.5m will result in 16 blocks as seen in Figure 7.1 and Figure 7.2. The general arrangement (Appendix G) together with the lightweight distribution provides the information to calculate the weight of the each dismantling block (Appendix F). It is calculated that each of the 16 dismantling blocks weigh less than 500T and their size will approximately be 18.5m by 16m. These blocks can very well be handled by the crane assumed at the recycling yard.

7.5.2.2 Discussion

This section of the chapter attempts to develop a cutting plan for the cargo section of the case ship using the limited amount of information available from the stability manual; and in the process, required improvements to the design features are pointed out and discussed in this section. The information available in the general arrangement plan, lightweight distribution and the stability manual of the case ship is used to plan the cutting operations of the ship. However, clearly no information is available either on the weights of the smaller sections that were grouped to form the large machinery and cargo sections of the case ship, or on how the smaller sections were grouped together. This is despite the fact that such information is critical to and is available during the ship's design and engineering phase. Such information, if well documented and kept on board in the digital form, can be immensely useful to plan the cutting operations of the ship recycling process.

Lifting a dismantling block, weighing up to 500 T can be dangerous if proper lifting supports are not available. Since, the position and number of small blocks is already known during the design and engineering phase, position of lifting supports for each block must also be determined during that phase. One option could be to weld steel rings at appropriate positions within the structure of each small block so that these rings can be used as lifting supports during the dismantling phase. Another option can be to determine the location(s) in each small block where it should be safe to lift. During the dismantling phase, a small hole can be cut in the structure at these precise locations, which can be used as lifting supports.

7.5.2.3 Lifecycle analysis

The two main design features discussed for reverse production include documenting the information on weights and location of small sections which are combined to form a large block, and putting in place the lifting supports on small sections during the design and engineering phase of the ship's lifecycle. This section of the chapter discusses the impact of these design features in terms of costs and benefits during various stages of the ship's lifecycle, which includes design and engineering phase, building or construction phase, operational phase and recycling phase.

The implementation of these two design features will definitely require an additional amount of work by designers during the ship's design and engineering phase. The amount of time required for planning the division of the ship into small dismantling blocks, documenting and determining the positions of lifting supports depends on the efficiency of the designers. It is assumed that two persons need two full weeks to define the dismantling blocks, to determine the position where the steel needs to be cut and to engineer the positions of the lifting supports. Also, another two weeks are assumed for an elaborate documentation and constructing a dismantling plan. This means a total of 320 man-hours are needed if a five day work week having eight hours a day is assumed. This figure can be translated into costs depending on the wages.

Similar to the design and engineering phase, an extra amount of work is also required to be done during the building phase of the ship's lifecycle. The places where the steel sections must be cut for block dismantling are required to be marked. Also, in some cases, the steel rings that may be used as lifting supports are required to be welded on to the ship's structure. The amount of time required to carry out such work depends on the efficiency of the workers whereas the cost depends on the wages, both of which differs from one yard to other.

The operational phase will be least affected by this concept. However, the marks pointing the places at which the sections were welded together must remain intact throughout the operational life of the ship. The ship's staff must take appropriate care to ensure the same. Any maintenance, repair or paint job undertaken in such areas must be carefully executed.

The benefits during the ship's recycling phase due to design changes to achieve reverse production include efficient cutting of a ship's hull, and prevention of incidents and accidents caused by falling pieces of a ship's hull. A ship built for reverse production can be dismantled efficiently because hull cutting operations can be planned easily based on the production plans and the marks on the ship’s structure where small sections were joined together. A well planned hull cutting operation, together with proper safety measures will certainly result in the prevention of accidents during the ship recycling operation. Apart from these benefits, an efficient cutting operation will be less time consuming. As a result, ship recycling yards can also save money due to reduced man hours.

However, certain yards might have to invest some amount of money to install high capacity cranes to make use of the concept of reverse production. The reason for this is the high capacities of cranes on ship building yards than on the recycling yards. It will be a one-time investment that will improve the efficiency of the ship recycling yard if all ships handled for recycling are designed to assist reverse production. For normally designed ships, recycling yards with high crane capacity can benefit from reduced time of operations during the primary cutting process.

7.5.2.4 Conclusion

The evaluation of the case ship with respect to reverse production planning resulted in recommending two design improvements. First, the weight and position of small sections of the ship must be physically marked on the ship’s structure and it must be documented as well. Second, either the use of lifting supports to lift these small sections or documenting the position where these sections must be lifted upon. The costs, benefits and other impacts of these design changes during each phase of the ship’s lifecycle are also discussed. During the recycling phase, ships designed to assist reverse production are likely to have more benefits than costs. These benefits include both economic and safety related benefits.

7.5.3 Modular accommodation

The current situation on the ship recycling yards is such that several health and safety related problems are encountered by the workers while working in the accommodation blocks of the end-of-life ships. In Alang, India, 40 percent of the total 257 deaths from 1991 to 2000 are caused by falling from heights or by falling objects (Kumar, 2009). Since other major causes of deaths such as fire, explosions, inhaling hazardous gases occur mostly in a ship’s cargo or machinery section, it can be assumed that working at heights is the major cause of death while working in a ship’s accommodation section.

The accommodation section must be designed taking the ship’s recycling phase in account. An improvement could be the use of modular units to build superstructure. Pre-fabricated units can be installed for different applications such as crew cabins, galley, hallways, etc. If these units are the size of standard containers such as TEUs and FEUs, they can be mass produced and easily transported to the shipyards. During ship recycling, they can be removed from the ship either for reusing, remanufacturing or recycling. The units of crew cabins can be reused as homes for local population. All units of accommodation block can also be remanufactured by repairing and remodelling to install on a new ship. For recycling, they can be brought ashore using cranes to dismantle the entire structure.

In an attempt to find a better design of accommodation pertaining to the needs of the ship's recycling phase, this section of the chapter refers to a highly innovative accommodation design which has been the subject of provisional patent application in Singapore. The referred design is generated by Fikkert et al. (2013), and is originally meant for offshore platforms (Appendix H). The aim of referring to such a design is to bring the attention of the ship designers and ship building industry towards existing innovative solutions. However, the referred design needs to be adapted suitably for implementing to the case ship, which can be carried out during the future research. Such research must also consider the likely impacts of new accommodation design on costs and benefits during each stage of a ship's lifecycle.

7.6 Case study 2: improving lightweight distribution

7.6.1 Research outline

The aim of this section is to develop a format of lightweight distribution which is useful for ship recycling, in addition to its intended usefulness for ship operation and navigation. This section aims to achieve this goal by following a three step reverse lifecycle analysis. The first step is to analyse the ship's recycling stage in order to understand the requirements of the ship recycling yards with respect to the ship specific information needed by them to draw a ship recycling plan. The second step is to focus on the operation stage and carry out a gap analysis of existing lightweight distribution in order to understand what information is missing and must be added to it to assist safe and environmentally conscious ship recycling. The third and final step is to analyse the ship's design and construction stage to understand how and what kind of information is stored so that the possibility of finding the missing information and improving the way it is stored can be explored. The research outline followed in this section is depicted by Figure 7.3.

7.6.2 Recycling stage

As per the requirements of Hong Kong convention and EU regulation on ship recycling, a ship specific recycling plan must be drawn before starting the work on the vessel. This recycling plan must describe how the ship recycling facility will recycle the specific ship in a safe and environmentally sound manner, covering the sequence of steps of the recycling process (IMO, 2011b). It is thus imperative to understand what kind of information is sought by ship recycling yards to develop such an effective ship recycling plan. It is also important that a recycling facility meets regulatory requirements in a cost effective manner. The planning for safe and economical operation of a recycling facility relies on knowing the quantities and types of materials that are required to be handled. A ship recycling yard usually extracts certain types of scraps from an end-of-life ship instead of breaking down every ship component to the lowest possible chemical element. For example, ship's machinery is not always cut to form ferrous scrap; it can be reused as it is, if possible whereas ship's electrical and electronic equipment are not always dismantled on site; they can be sold to companies responsible for downstream recycling. A typical scheme of types of scraps generated from an end-of-life ship is shown in Figure 7.4 (Andersen et al., 2001). The removal of hazardous materials and handling of hull sections is also a vital part of the ship recycling process (Hiremath et al., 2015). Thus, a ship recycler mainly needs three types of ship specific information which includes (1) the quantity and location of hazardous materials, (2) weights of hull sections and (3) the quantity of various types of scraps.

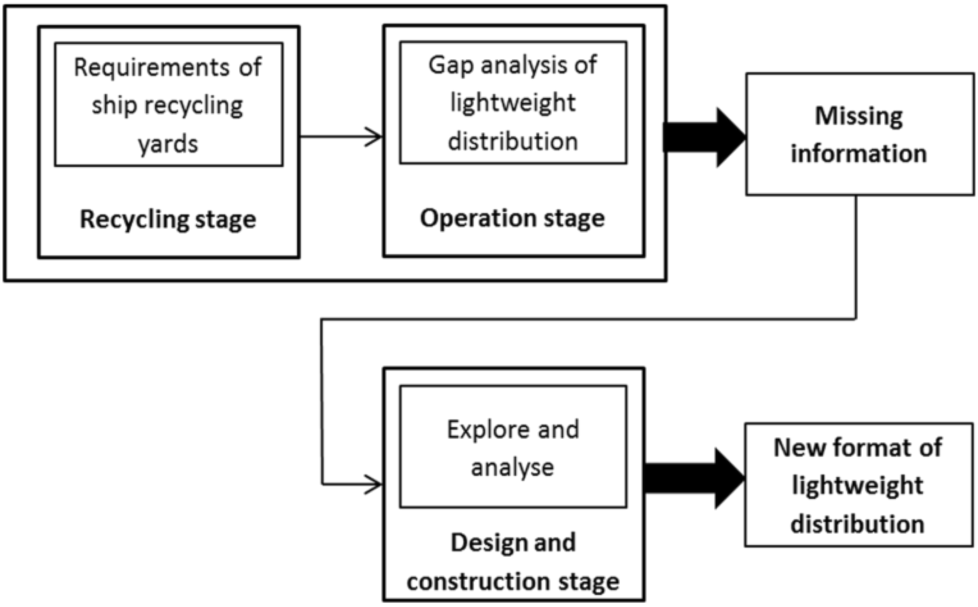


Figure 7.3: Research outline to develop a new format of the lightweight distribution

Although ship's IHM is intended to provide information on hazardous materials, information about the quantity of various types of scraps and weights of hull sections is difficult to obtain at the end of ship's life. However, as discussed in Chapter 4 (Jain et al., 2016b), to some extent such information is recorded in ship's lightweight distribution to enable safe navigation and operation of the ship but it is not intended to support ship recycling. This section will continue further with the gap analysis of the lightweight distribution of the case ship with respect to the information sought by ship recyclers. The gap analysis is carried out to ascertain what information is available from each element of the lightweight distribution with respect to the type of scrap.

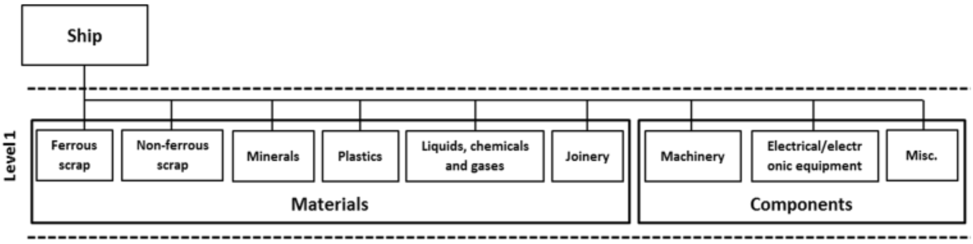


Figure 7.4: Types of scraps generated during the ship recycling process

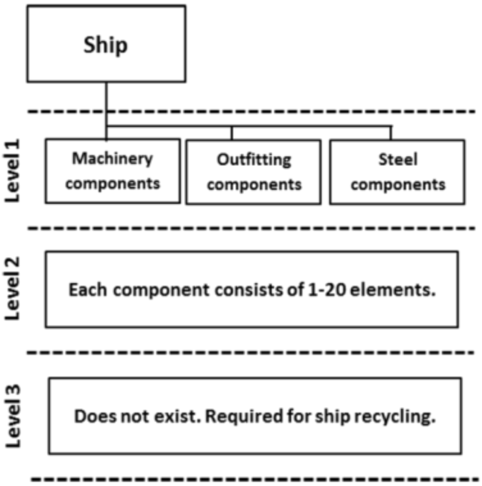


Figure 7.5: The format used for the case ship's lightweight distribution

7.6.3 Operation stage

7.6.3.1 Lightweight distribution

The international rules for the general contents of the stability manual (DNV, 2011) require lightweight particulars of a ship to be recorded in its stability manual to assist day to day ship operation (Barrass and Derrett, 2011). The lightweight normally consists of three main elements (1) Steel weight (W_s): steel hull and superstructure, (2) Outfitting weight (W_o): accommodation, deck fittings, piping, lifeboats etc., and (3) Machinery weight (W_m): main propulsion and auxiliaries such as generators, compressors, boilers etc. A margin is also incorporated, depending on the level of uncertainty of the lightship estimate (Molland, 2011).

The elements of lightweight distribution of the case ship provided in its stability manual (CarlBro, 2006) are shown in Table 7.1. The result of gap analysis is also recorded there. The distribution shows that case ship's lightweight is calculated by following a two level divisional structure (Figure 7.5). Level 1 divides the ship into three main categories – machinery components (M), outfitting components (U) and steel components (S) with a correction factor (X). Each of these components of level 1 consists of few elements forming the level 2 of the structure. In total, 36 elements are combined to calculate the lightweight of the case ship.

Table 7.1: LDT distribution of the case ship as given in its stability manual with gap analysis for ship recycling

Elements	**Weight (T)**	**Gap Analysis for ship recycling w.r.t. the type of scrap**
MACHINERY COMPONENTS		
M01: Machinery piping	95.0	Not enough information
M02: Electrical	25.0	Not enough information
M03: Bridge equipment	6.0	Electrical and electronic scrap
M04: Tools and spares	15.0	Ferrous scrap
M05: Main engine	220.0	Machinery
M06: Shafts	28.0	Ferrous scrap
M07: Propeller	17.0	Non-ferrous scrap
M08: Auxiliary engines	38.0	Machinery
M09: Machinery comp	80.0	Not enough information
M10: Machinery equip	115.0	Not enough information
OUTFITTING COMPONENTS		
U01: Crane 1	57.0	Machinery
U02: Crane 2	57.0	Machinery
U03: Crane 3	57.0	Machinery
U04: Crane 4	57.0	Machinery
U05: Hatches	880.0	Ferrous scrap
U06: Outfit for	220.0	Not enough information
U07: Outfit Mid	200.0	Not enough information
U08: Outfit Aft	500.0	Not enough information

U09: Paint and cathodes	130.0	Not enough information
STEEL COMPONENTS		
S01: Forpeak Fcle	320.0	Ferrous scrap
S02: Bhd CH1-CH2	182.0	Ferrous scrap
S03: Bhd CH2-CH3	198.0	Ferrous scrap
S04: Bhd CH3-CH4	198.0	Ferrous scrap
S05: Bhd CH4-CH5	132.0	Ferrous scrap
S06: Cargo section	5600.0	Ferrous scrap
S07: Machinery section	1070.0	Ferrous scrap
S08: Casing funnel	80.0	Ferrous scrap
S09: Accommodation	320.0	Ferrous scrap
S10: Hatch coaming	205.0	Ferrous scrap
S11: Crane pedestal 1	18.0	Ferrous scrap
S12: Crane pedestal 2	18.0	Ferrous scrap
S13: Crane pedestal 3	18.0	Ferrous scrap
S14: Crane pedestal 4	18.0	Ferrous scrap
S15: Deck house Fr. 72	12.0	Ferrous scrap
S16: Deck house Fr. 144	12.0	Ferrous scrap
CORRECTION FACTOR		
X01: Tol and Marg	-203.9	Ferrous scrap
Total	11044.1	

7.6.3.2 Gap analysis

The results of gap analysis tabulated in Table 7.1 determines that most elements of lightweight distribution can be clearly classified into a type of scrap, for example, elements S01-S16 (steel components) forms ferrous scrap, elements U01-U04 (cranes), M05 (main engine) and M08 (auxiliary engines) forms machinery stream and element M07 (propeller) form non-ferrous scrap, etc. On the other hand, many elements lack the level of detail required by the ship recycling yards to determine what type of scrap would be generated from each of those elements. Such elements include machinery piping (M01), electrical (M02), machinery component (M09), machinery equipment (M10), outfitting for-ward (U06), outfitting midship (U07), outfitting aft (U08) and paint and cathodes (U09) as shown in Table 7.2.

Conclusively, although ship's lightweight distribution provides a lot of information on weights of sections and types of scraps, gap analysis concludes that it does not fulfil the requirements of ship recyclers completely. This shortcoming must be overcome by improving the existing format of lightweight distribution to suit the needs of ship recyclers without hampering its usefulness for ship operation and navigation. The existing two level formats can be improved by adding a detailed level (level 3) so that each element of level 2 can be classified into one or the other category of scrap shown in Figure 7.4. The new level can be developed by analysing the elements of existing distribution lacking details needed for ship recycling (Table 7.2).

Table 7.2: Elements of lightweight distribution lacking the desired level of detail for ship recycling

Elements	**Desired level of detail for ship recycling**
M01: Machinery piping	Weight of ferrous and non-ferrous piping
M02: Electrical	Weight of cables and electrical equipment
M09: Machinery comp	Weight of individual components
M10: Machinery equip	Weight of individual equipment
U06: Outfit for	Weight of individual components
U07: Outfit mid	Weight of individual components
U08: Outfit aft	Weight of individual components
U09: Paint and cathodes	Weight of paint and cathodes separately

7.6.3.3 Missing information

After analysing the recycling and operation stage of ship's lifecycle and comparing the requirements of ship recycling yards with the information available in ship's lightweight distribution, missing information can be derived on the basis of analysis of elements lacking the desired level of detail for ship recycling. The composition of such elements must be analysed in order to understand to which scrap stream each of these elements belong to. For example, the element M01, machinery piping may comprise the weight of ferrous and non-ferrous piping; the element M02, electrical may comprise the weight of copper cables (non-ferrous scrap) and electrical equipment; the element M09, machinery comp may comprise the weight of ladders, floor gratings, floor plates and railings forming the ferrous scrap and heat and noise insulation in the engine room forming the mineral scrap stream (Bertram and Schneekluth, 1998, Papanikolaou et al., 2009); the element M10, machinery equip may comprise the weight of machines and equipment in the engine room except the ones reported individually in the lightweight distribution; the element U09, paint and cathodes certainly comprise the weight of paint forming miscellaneous scrap stream and cathodes forming the non-ferrous scrap while the elements U06 to U08 (outfit) may comprise the weight of various items made of different materials forming almost all the types of scraps (Jain et al., 2016b).

This derived knowledge about the requirements of ship recycling yards related to types of scraps forms the desired level of detail required for ship recycling. It can be used to modify the elements lacking details for ship recycling so that a new format of the lightweight distribution can be developed. The desired level of detail for each of these elements can be achieved if the weights of individual components of these elements are known. Conclusively, if those 8 elements lacking details for ship recycling (Table 7.2) are replaced with new detailed elements to form a new format of lightweight distribution, ship recycling yards would have enough information to plan the ship recycling process. In the next section, the design and construction stage of ship's lifecycle is analysed to understand if the required information is available or not.

7.6.4 Design and construction stage

The weight estimation of various items which make up the lightweight is an important factor in the design process because they influence the technical characteristics such as draught and deadweight, and are often used as the basis for cost estimation (Molland, 2011). At the preliminary design stage, usually the empirical approximations which relate the weight components to the principal ship particulars (such as dimensions and power) are used for estimating the lightweight elements. With a little extra effort and time, it is possible to derive reasonably accurate estimates of these weights at the detailed design stage, particularly during and just after the construction (Molland, 2011).

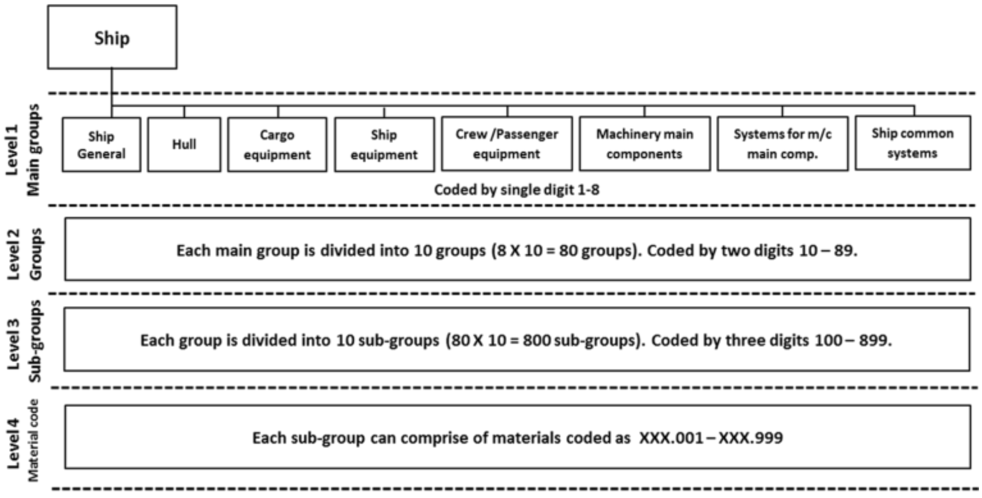


Figure 7.6: The format used for the concept of work breakdown structure of a ship

Such information can easily be derived because most ship building yards worldwide use the concept of either product or system work breakdown structure (WBS) for the purpose of cost estimation, weight estimation and project management. The WBS is a progressive hierarchical breakdown of a project into smaller and smaller work packages to the lowest practical level at which various construction, engineering and management functions can be reasonably applied (Li et al., 2016b). For ships, it is used to divide the total ship production process into component parts in order to control the process (Storch and Lim, 1999). The same WBS is also used by ship owners for ship's operation and maintenance within the ship's planned maintenance system. The most widely used WBS in ship building industry is the SFI Group System developed at the Ship Research Institute of Norway in 1972 which is commercially available from SpecTec (SpecTec, 2015). The WBS of SFI Group System divides a ship into 10 main groups from 0 to 9. Each of the main groups (1 digit) consists of 10 groups (2 digit) and each group is divided further into 10 sub-groups (3 digit) as depicted by Figure 7.6.

Table 7.3: A part of work breakdown structure typically used by ship building yards

2 FURNISHING, INVENTORY AND INSULATION
21 Panelling, Ceiling
211 Wall and separation panel
211.001 Modular wall and separation panel
211.002 Non-modular wall and separation panel
212 Ceiling system
22 Insulation bulkheads, decks and pipelines
221 Insulation of bulkheads and decks
222 Insulation of pipelines
23 Furnishing and outfit public spaces
24 Furnishing and outfit workshops, stores
3 ELECTRICAL, NAUTICAL COMMUNICATION SYSTEMS
31 Electrical distribution system
32 Communication and entertainment
33 Lighting installation

A part of typical WBS used by ship building yards is shown in Table 7.3. The useful information from a ship recycling yards' point of view, available within ship's WBS include the weights of individual components forming the weight of elements lacking details for ship recycling. This includes the weight of components such as piping, cabling, insulation, anchor, chain, windlass, mooring winch, steering gear etc. A closer look at the given example of WBS clarifies that such information is clearly available. For example, component number 221 and 222 denotes the weight of insulation of bulkheads, decks and pipelines. Conclusively, weights of individual components of a ship forming the total lightweight are available at a detailed enough level to meet the requirements of a ship recycling yard. It is just the matter of presenting the lightweight distribution in a level that is detailed enough to provide the information required by ship recycling yards at the end of ship's life. The effort and time spent by ship building yards to derive such information in the ship design stage can improve the way ship recycling is currently carried out.

7.6.5 New format of lightweight distribution

As per the analysis so far, it is known that ship recycling yards need three main types of information to prepare an effective ship recycling plan. The information on hazardous materials is available through ship's IHM while the information regarding the weights of hull sections is available through the steel components of the lightweight distribution of the ship whereas the information on the quantity of various types of scraps is not readily available for all the elements of the lightweight distribution. In total, 8 elements are found to be lacking the details for ship recycling. The missing information on these elements can be derived from the WBS used during the ship design and construction stage. The new format of the lightweight distribution can be developed by improving these 8 elements in such a way that new elements provide enough information to ship recycling yards.

In the existing format, the elements related to steel components provides satisfactory information to the ship recycling yards whereas few changes are required to the elements related to machinery and outfitting components (Table 7.2). These changes must be made keeping in mind the missing information derived in section 7.6.4. Therefore, machinery components should have new elements such as ferrous and non-ferrous piping (derived from M01), electrical cables and electrical equipment (derived from M02), machinery equipment, insulation, railings and floor plating (derived from M09 and M10) whereas outfitting components should have new elements such as ferrous and non-ferrous outfitting, individual machinery, electrical cables, electrical equipment, insulation and wooden panelling in forward, mid and aft areas of the ship (derived from U06 to U08). Paints and cathodes should be weighed separately (derived from U09).

The new elements to be added to the existing lightweight distribution of the case ship replacing 8 elements lacking details are proposed in Table 7.4.

Table 7.4: Elements proposed to be added to the lightweight distribution of the case ship

MACHINERY COMPONENTS
M01: Machinery piping ferrous
M02: Machinery piping non-ferrous
M03: Electrical cables machinery room
M04: Electrical equipment machinery room
M05: Insulation machinery room
M06: Railings and floor plates machinery room
M07: Weight of each machinery
OUTFITTING COMPONENTS
U01: Outfit Fwd/Mid/Aft ferrous
U02: Outfit Fwd/Mid/Aft non-ferrous
U03: Weight of each machinery Fwd/Mid/Aft
U04: Electrical cables Fwd/Mid/Aft
U05: Electrical equipment Fwd/Mid/Aft
U06: Insulation Fwd/Mid/Aft
U07: Wooden panelling Fwd/Mid/Aft
U08: Paint
U09: Cathodes

In conclusion, the eight elements lacking details are replaced by sixteen new elements that provide detailed information to ship recycling yards without distorting the information already available in the existing lightweight distribution. This improves the usefulness of the lightweight distribution of the case ship for ship recycling yards. The proposed format can be used to standardize the elements for bulk carriers. At the moment, elements differ from ship to ship due to lack of standardized format. The level of details of the elements depends on the procedures employed by the shipyard. The elements standardized by international regulations, for each ship type, can improve the usefulness of the lightweight distribution.

7.6.6 Discussion and conclusion

The new format of lightweight distribution will certainly have impact on various stakeholders involved during the lifetime of the vessel. The stakeholders involved include shipyard which carries out lightweight calculation and prepares the required documents, classification society which verifies and certifies the authenticity of lightweight calculation and documents with respect to applicable regulations, ship owner who needs accurate information about his ship, and ship's crew who needs such information to maintain ship's stability to ensure the safety of cargo, crew and ship.

The purpose of lightweight distribution for ship's design and construction phase is to accurately calculate the lightweight and subsequently the deadweight of the ship whereas during the ship's operation phase it provides sufficient information to ship's crew to operate the ship in compliance with the stability requirements imposed by relevant regulations. As far as recycling phase of a ship's lifetime is concerned, although lightweight distribution is found to be useful to some extent, up until now it is not intended to provide any information to recycling yards.

The new format of lightweight distribution ensures that ship recycling yards become one of the beneficiaries without affecting the existing stakeholders. Although shipyards will have to calculate the weights and centres for an increased number of elements, it will ensure increased accuracy of the lightweight calculation. An accurate lightweight calculation is beneficial for all the stakeholders. More importantly, it will help recycling yards develop a ship specific recycling plan in accordance with upcoming regulations on ship recycling such as Hong Kong convention and EU regulation and thus improve the prevalent ship recycling practices.

The key to safe and environmentally sound ship recycling lies in the well-designed ships that are safe and easy to recycle. A ship can become easy to recycle if information about what it contains is available to the ship recyclers. Although Hong Kong convention on ship recycling can assist ship recyclers in achieving safe recycling by making ship owners responsible to provide ship specific information, there is a lot that can be improved about the way ships are designed in order to enhance ship recycling. The onus should be on ship builders to record as much information as possible during the ship design stage because an improved ship design not only refers to easy to recycle ship structure but also refers to easy to obtain information at the end of ship's life. It is easier to store information on ship's materials during the ship design and construction stage than to investigate about it during the recycling stage.

This case study explained how ship's lightweight distribution can be an important document to store information for ship recyclers. The study reveals that lightweight distribution of the existing case ship (bulk carrier) does not provide enough information to ship recyclers to develop an effective ship recycling plan. Thus, a new format of the lightweight distribution for bulk carriers is proposed. This format is intended to support ship recycling planning in accordance with the Hong Kong convention without affecting the design and operational phase of ship's lifetime. It is also intended to fill the gap in the existing regulations on ship's stability manual which prescribe its general contents to include "preliminary lightship particulars based on an estimate or sister vessel" (DNV, 2011) but does not define the number of elements of the lightship particulars.

7.7 Summary and concluding remarks

This chapter extensively described the concept of design-for-recycling within the context of ships. Two main aspects of the concept, i.e., structural and documental changes are discussed in reference to a handymax bulk carrier as a case ship. Based on the literature survey, eight major design changes that can improve ship recycling are established. Out of these changes, two, modular accommodation and reverse production are discussed with reference to the case ship.

An innovative design for modular accommodation based on accommodation for offshore platforms is proposed. Further research is needed to implement this concept. The stability manual of the case ship is analysed to discuss the concept of reverse production. The analysis found that the information provided in the stability manual is not enough to follow reverse production. The similar conclusion was also drawn from Chapter 4 with respect to material quantification of the ship. Based on these two conclusions, the lightweight distribution provided in the stability manual of the case ship is analysed for changes to make it suitable for the ship's dismantling stage. A new structure for the ship's lightweight distribution is proposed as a documental change required during the ship's design stage.

The work carried out in this research is limited to the handymax bulk carrier because of unavailability of ship related information such as stability manual and general arrangement for other ship types. It would be interesting to analyse the stability manuals of other ship types to understand how much information is available with respect to the ship's recycling stage and what structural and documental changes must be made to improve the ease of dismantling of those ships.

CHAPTER 8

CONCLUSIONS

"A conclusion is the place where you got tired thinking."

- Martin Henry Fischer (1879-1962), Physician

This dissertation investigated how to improve the competitiveness of green ship recycling yards against substandard ship recycling yards. The probable solutions to the research problem are derived in Chapter 3 which sets up the course of action of this research. As a result, a two dimensional approach is followed, which means both ship-based and yard-based strategies are investigated. Chapters 4 and 7 present the ship-based strategies whereas Chapters 5 and 6 present the yard-based strategies.

This chapter first combines the results of the Chapters 4 through 7 to understand the answers obtained to the research sub-questions during the course of this dissertation. It also discusses the implications of the suggested strategies/concepts/measures on recycling yards in different locations. Based on the answers to the research sub-questions and the implications to the global yards, a discussion is carried out to understand the extent to which the main research question is answered. Then, recommendations for the future direction of research as well as for ship designers and ship recyclers are provided. Lastly, the originality and the contribution of the research to the existing knowledge are discussed.

8.1 Results and conclusions

The main research question of this dissertation was *how green ship recycling yards can improve their competitiveness against substandard ship recycling yards?*

To answer this question, it is imperative to discuss the results obtained in Chapters 4 through 7 so that the answers to the research sub-questions can be obtained and the implications of these results within the context of the global ship recycling industry can be inferred.

8.1.1 Answers to research sub-questions

The research carried out in this dissertation resulted in finding the answers to research sub-questions, as discussed below.

1. What is the current state of the global ship recycling industry and what is the difference between the green and substandard ship recycling?

Chapter 2 of the dissertation discussed that there is a trade-off between environmentally sound green ship recycling and income generated by selling the vessel. Therefore, the majority of the vessels are recycled without taking much care of the environment and safe working conditions for the workers. Major contributing factor to it is the high operational costs of green ship recycling yards as compared to the substandard yards. The chapter also showed that regulations are proposed by international organizations (EU and IMO) to establish minimum set of requirements for yards, but they are not yet applicable worldwide.

2. How to decide what measures can be applied to a ship recycling yard to achieve the stated objectives of the research?

Chapter 3 of the dissertation concludes that the principles of the concept of cleaner production defined by UNEP can be used to identify the measures applicable to a ship recycling yard for improving its competitiveness (and achieving the objectives of this research). The similarity of the ship recycling process to a (reverse) production process allowed us to analyse the concept of cleaner production with respect to ship recycling. The effectiveness of the concept in meeting similar objectives in other industries is also a driving force behind using it for this research.

3. What are the quantities and types of material streams available on an end-of-life ship?

The quantities and types of material streams of an end-of-life ship can be estimated using the ship’s lightweight distribution as an input to the material quantification model discussed in this dissertation. The ship’s lightweight distribution is usually available within its stability manual. However, since there is no standard format of a ship’s lightweight distribution, the required information is not available in detail in all cases. Therefore, the dependability of the model on the information available in a ship’s lightweight distribution is its major drawback and prevents it from being used on all ships. Hence, standardizing the format of lightweight distribution will be useful.

4. How can recycling yards plan the disintegration of a vessel into recyclable products and waste?

An important step to plan the disintegration of a ship into recyclable products and waste is to determine – what does a ship contain and in what quantity. This is fulfilled by the material quantification model explained in Chapter 4. Another step is to determine and understand the flows of materials through various stages of the recycling process. Chapter 5 of the dissertation developed and discussed a material flow analysis (MFA) model which can be used by yards to plan the recycling process by determining the quantities of recyclable products and waste depending on the properties of the process employed and the prevailing market conditions.

The model resulted in determining 96.6% LDT as the maximum amount of recyclable products for the handymax bulker.

5. How can recycling yards turn the waste generated during the recycling process into revenue?

Ship recycling yards can turn the waste generated during the recycling process into revenue by selling the useful products produced by a plasma gasification plant operating on the waste generated on the yard as feedstock. Chapter 6 investigated the economic effectiveness of using a plasma gasification plant on a large ship recycling yard. The results suggest that such a plant can effectively be used on ship recycling yards having more than one million tons annual dismantling capacity. In fact, such yards can even offer an extra amount of up to $7 per LDT to ship owners for buying end-of-life ships, depending on the plant size and the recycling rate.

6. What design changes can be made to a ship to increase the cost-effectiveness of green ship recycling?

Chapter 7 of the dissertation described that the two types of design changes, structural and documental, can be made to a ship for improving the cost-effectiveness of green ship recycling. The feedback from the recycling stage to the design stage of the ship's lifecycle is important to determine the exact design changes required to improve ship recycling.

8.1.2 Integration of results – inferences for the global ship recycling industry

So far, we discussed that the suggested measures such as material quantification of end-of-life ships, material flow analysis on a ship recycling yard, plasma gasification plant for waste disposal and design-for-recycling are likely to improve the ship recycling planning and revenues of green ship recycling yards. This will allow them to offer a higher price to ship owners for buying end-of-life ships. We also discussed (Chapter 6, case study 2) that the upgrade of non-green yards to green yards will have a negative impact on the offer price.

The applicability and the effect of different measures will differ depending on the location of the ship recycling yard. Therefore, this section discusses the impact of suggested measures in the context of global ship recycling industry. Two types of comparisons can be made; first, between the green and non-green yards of the same country and second, between the green or non-green yards of different countries.

As discussed in the case study 2 of Chapter 6, the upper bound for the reduction in offer price due to the upgrade of pier-breaking yards (scenario 1) is approximately 10 \$/LDT, while for slipway yards (scenario 2), it is approximately 20 \$/LDT. By virtue of yard types, these values correspond to the Chinese and Turkish yards, respectively. Considering the results of upgrading basic pier/harbour (scenarios 1a/2a), the value of 30 \$/LDT for the yards in the Indian subcontinent seems realistic. These values can be used to compare the green and non-green yards of the same country, considering the current offer prices (Mar 2017) given by GMS (2017) to be of non-green yards (Figure 8.1).

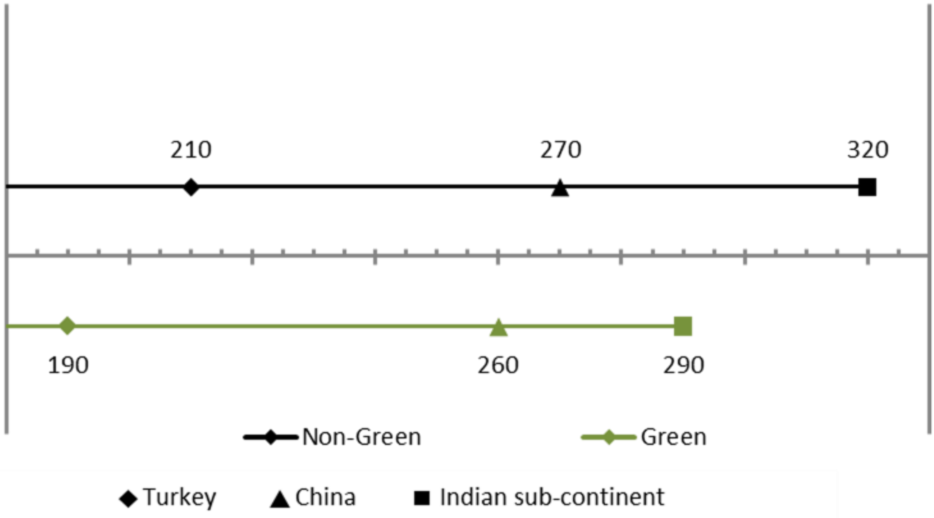


Figure 8.1: The prices offered (\$/LDT) for end-of-life ships by green and non-green yards in various countries (based on GMS (2017) for non-green yards and Chapter 6 for green yards)

Clearly, Figure 8.1 shows that the Indian subcontinent yards are likely to continue to offer a higher price than the Chinese or Turkish yards even after complying with the Hong Kong convention. However, the gap between the offer prices of Chinese and Indian subcontinent yards is likely to reduce sharply, mainly due to high compliance cost for the subcontinent yards. Nevertheless, the subcontinent yards must continue to upgrade their infrastructure as they are likely to hold on to the economic advantage of high offer prices than China and Turkey.

As discussed in the case study 1 of Chapter 6, a plasma gasification plant can be installed on large ship recycling yards to increase the offer price. Since, Turkish and Indian yards are mostly small to medium sized yards; they cannot benefit from this measure. However, owing to their large size, green yards in China can avail its benefits. As a result, the Chinese green recycling yards can offer about $5 per LDT more, which will effectively bridge the gap between the offer price of green and non-green yards in China by about $5 per LDT (Figure 8.2).

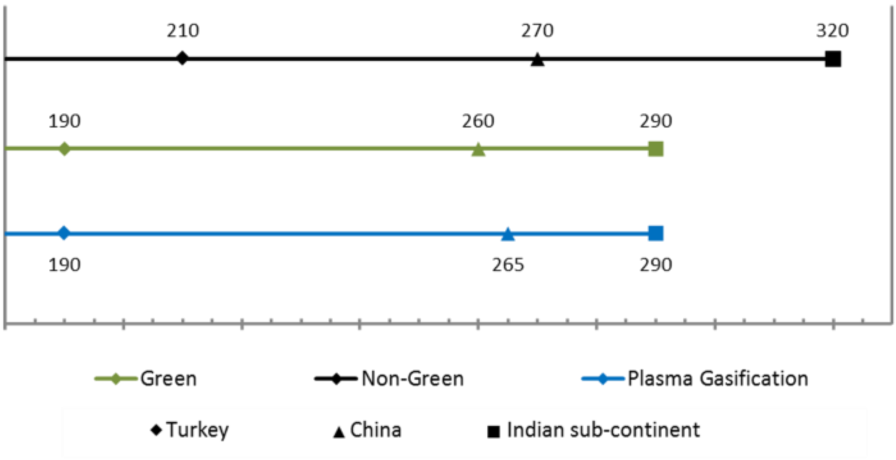


Figure 8.2: The prices offered (S/LDT) for end-of-life ships by green yards in various countries compared with the offer price when the plasma gasification plant is used in China

Effectively, the use of plasma gasification plants will also bridge the gap between the offer price of Chinese green yards and Indian subcontinent green yards, although minimally (as seen in Figure 8.2). This gap can further be reduced if the regulations in the subcontinent countries are tightened to prohibit the recycling of hazardous materials such as asbestos. It will not only reduce the revenue but also increase the cost of disposal for the subcontinent yards. An improved availability of downstream second hand market in China will also be impactful.

Other measures, such as design-for-recycling and improved planning due to material quantification and material flow analysis, are applicable to all yards, irrespective of their location and the recycling process employed. Therefore, their impact on reducing the gap between the offer prices of the green and non-green yards in a country or between the yards of two countries seems unquantifiable. However, such measures are likely to streamline the recycling operations, which, in-turn, will improve the offer prices in general.

Moreover, a non-green yard applying such planning-related measures cannot be foreseen as they lack expertise and willingness to improve their processes. This will allow a green yard to improve its competitiveness against a non-green yard in the same country.

8.1.3 Answer to the main research question

The main research question of this dissertation was *how green ship recycling yards can improve their competitiveness against substandard ship recycling yards?*

As per the discussion above, we can conclude that the green ship recycling yards can improve their competitiveness against substandard yards by planning the ship recycling process in a better way using the material quantification model and the material flow analysis model developed and discussed in this dissertation, which in turn is expected to reduce the costs of the recycling process, and by generating more revenue by using a plasma gasification plant to process the waste generated at the yards. The structural and documental changes to a ship design are also likely to be beneficial.

However, it is worth emphasizing that improving the competitiveness of a yard located in one country against a yard located in another country is not feasible due to perpetual local factors. Also, as every suggested measure is not applicable to the yards located in different countries, results differ from location to location. Therefore, development and enforcement of a robust regulation is important to improve the market share of green yards. For example, mandatory use of EUSRR-approved yards to recycle EU-flagged ships. However, loopholes such as the ability of owners to change the flag of ships to a non-EU country just before the end of a ship’s life must be plugged.

8.2 Recommendations

This section of the dissertation is divided into two parts; first, the recommendations for the future research based on the limitations and drawbacks of this research are presented, and second, the recommendations for ship recyclers, ship designers and other industry stakeholders to improve the ship recycling industry are presented.

8.2.1 Future research related

The material quantification model discussed in this dissertation is based on the lightweight distribution of a handymax bulk carrier, which was not found sufficiently adequate to quantify material streams accurately. Therefore, a new format of the lightweight distribution was suggested. To testify the accurateness of the new format, further research is required wherein implementation of the new format to new build ships can be investigated. Furthermore, it would be interesting to investigate the existing formats of lightweight distributions of other ship types. If required, new formats can be suggested per ship type basis.

In this dissertation, the material flow analysis is carried out on the basis of certain market related assumptions which may not represent an existing yard. Also, it is carried out for only one ship. However, in reality, such a situation may arise seldom. Therefore, further case studies on MFA must be carried out on the basis of real life situations involving more than one ship, which may belong to the same or different ship types.

The possibility of increasing revenues for ship recycling yards is investigated for plasma gasification plants only, based on their superiority over other waste-to-energy technologies. However, owing to their very high capital costs they are suitable only for large recycling yards. It would be interesting to find the impact of other waste-to-energy technologies especially on small and medium sized yards. Therefore, in future some research can be carried out on the same.

Furthermore, the possibilities of using the products generated by a plasma gasification plant for ship recycling operations can be explored. For example, hydrogen separated from syngas can be used to operate yard vehicles and machinery running on hydrogen fuel cell. A detailed technical and economic feasibility analysis will be required for the same.

8.2.2 Stakeholders related

The following recommendations are suggested for various stakeholders of the ship recycling industry:

1. Before commencing the recycling operations, a ship recycling yard must plan the recycling process using the analytical tools suggested in this thesis, i.e., the material quantification model and the material flow analysis.
2. The small and medium sized yards may still benefit from a plasma gasification plant if they are able to find sufficient sources of waste, potentially nearby industries or even a municipality. They can then operate on the principles of industrial symbiosis by exchanging useful products such as electricity, vitrified slag, chemicals, etc. with waste.
3. The ship recycling yards must collect and analyse ship related documents such as stability manual, lightweight distribution, finished plans, piping diagrams, section drawings, equipment manuals, etc., to plan the ship recycling process.
4. The collection of ship recycling process related data such as the amount of different types of material streams generated and the number of incidents and accidents can help improve the material quantification model and the future ship designs, respectively.

5. The shipyards must collaborate with leading recycling yards around the world to gather the feedback relating to the required changes in the ship design that may improve the ship recycling process.
6. It is recommended that the suggested format of the lightweight distribution be standardized through legal instruments such as IMO codes and IACS guidelines. As such, there is no standard format of the lightweight distribution used by various shipyards. Thinking ahead, the proposed format should also be updated in such a way that the ship’s lightweight can fully be distributed up to the material’s level contrary to the partial distribution using the proposed format.
7. For ship owners, shipyards, and classification societies, it is recommended that a consensus should be made amongst them to decide on the ownership of the ship’s documents such as stability manual, lightweight distribution, inventory of hazardous materials and others. This will help them share such data with ship recycling yards for planning the ship recycling process and also with researchers for further analysis.

8.3 Originality and contribution to the existing knowledge

Most ship recycling related research is focussed on assessing the health, safety and environmental impacts of the recycling process. Contrarily, this thesis explored and analysed methods and technologies to improve the existing ship recycling processes. The basis for the entire research presented here is the application of the concept of cleaner production, which is a pioneering approach in the context of recycling end-of-life ships. It is especially suitable as it focusses not only on the processes, but also on the equipment and products.

A result is the proposal of an innovative method to quantify material composition of end-of-life ships, which is a step ahead of the existing regulatory recommendation and practice of identifying only hazardous materials. This thesis also recommended planning the recycling process using the MFA approach, which is prevalent in other industries but has thus far found no application within the realm of ship recycling. The proposed use of plasma gasification technology to manage wastes on recycling yards can be a game changer for green ship recycling subject to the reduction of capital costs of such a technology. It will help not only improve the offer price but also utilize end-products within the recycling process itself, making it truly circular.

APPENDICES

Appendix A: Goal-seek model for calculating the annual cash flow

The model is explained using the screenshots of the Excel sheets of the model. The initial state of the model is shown in Figure A.1. The initial inputs to the model include discount rate and the investment amount required (cash flow for year 0). This amount is preceded by a negative sign because it is a negative cash flow for a ship recycling yard. The cash flows from year 1 to year 20 are assumed to be equal. They have no value in the initial state of the model. The discount factor is calculated using the following formula.

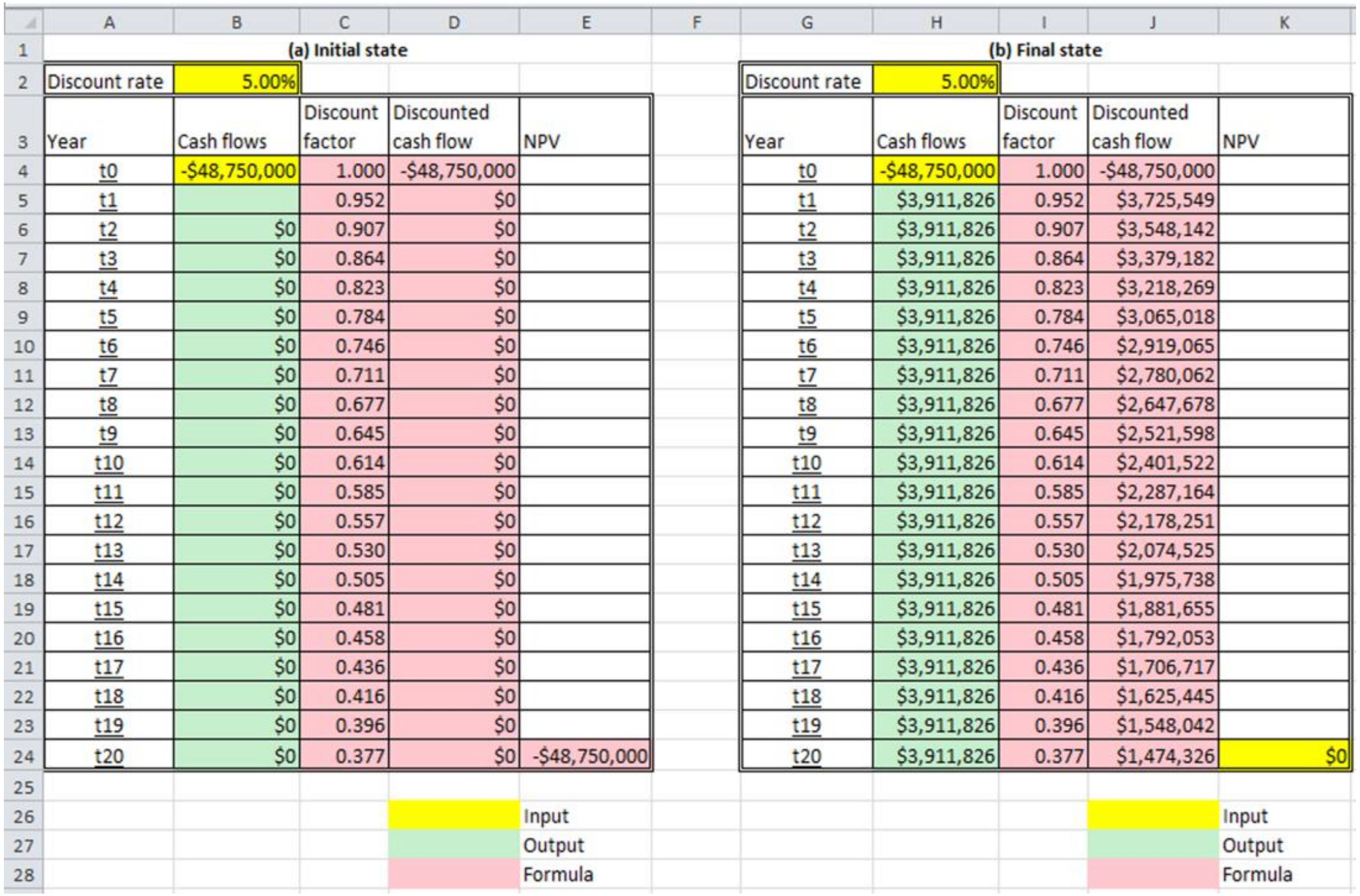
$$\text{Discount factor (DF)} = \frac{1}{(1+R)^n} ,$$

where R = discount rate and n = year.

The discounted cash flow is calculated by multiplying the annual cash flow with the discount factor. The net present value (NPV) is calculated by adding all the discounted cash flows from year 0 till year 20.

The model is executed by using the ‘goal-seek’ function of the MS Excel program to determine the values of annual cash flows from year 0 till year 20. For this purpose, the value of NPV is set to zero in the ‘goal-seek’ function.

The final state of the model after execution is shown in Figure A.1(b). It shows the amount of annual cash flows ($3,911,826) for the initial investment of $48,750,000 at 5% discount rate, as calculated by the Excel program.



(a) Initial state

Discount rate	5.00%			
Year	Cash flows	Discount factor	Discounted cash flow	NPV
t0	-$48,750,000	1.000	-$48,750,000	
t1		0.952	$0	
t2	$0	0.907	$0	
t3	$0	0.864	$0	
t4	$0	0.823	$0	
t5	$0	0.784	$0	
t6	$0	0.746	$0	
t7	$0	0.711	$0	
t8	$0	0.677	$0	
t9	$0	0.645	$0	
t10	$0	0.614	$0	
t11	$0	0.585	$0	
t12	$0	0.557	$0	
t13	$0	0.530	$0	
t14	$0	0.505	$0	
t15	$0	0.481	$0	
t16	$0	0.458	$0	
t17	$0	0.436	$0	
t18	$0	0.416	$0	
t19	$0	0.396	$0	
t20	$0	0.377	$0	-$48,750,000

🟨 Input
🟩 Output
🟥 Formula

(b) Final state

Discount rate	5.00%			
Year	Cash flows	Discount factor	Discounted cash flow	NPV
t0	-$48,750,000	1.000	-$48,750,000	
t1	$3,911,826	0.952	$3,725,549	
t2	$3,911,826	0.907	$3,548,142	
t3	$3,911,826	0.864	$3,379,182	
t4	$3,911,826	0.823	$3,218,269	
t5	$3,911,826	0.784	$3,065,018	
t6	$3,911,826	0.746	$2,919,065	
t7	$3,911,826	0.711	$2,780,062	
t8	$3,911,826	0.677	$2,647,678	
t9	$3,911,826	0.645	$2,521,598	
t10	$3,911,826	0.614	$2,401,522	
t11	$3,911,826	0.585	$2,287,164	
t12	$3,911,826	0.557	$2,178,251	
t13	$3,911,826	0.530	$2,074,525	
t14	$3,911,826	0.505	$1,975,738	
t15	$3,911,826	0.481	$1,881,655	
t16	$3,911,826	0.458	$1,792,053	
t17	$3,911,826	0.436	$1,706,717	
t18	$3,911,826	0.416	$1,625,445	
t19	$3,911,826	0.396	$1,548,042	
t20	$3,911,826	0.377	$1,474,326	$0

🟨 Input
🟩 Output
🟥 Formula

Figure A.1: Cash flow calculation model (a) Initial state (b) Final state after execution

Appendix B: What-if analysis of a 250 TPD plasma gasification plant on ship recycling yards of various dismantling capacities at different discount rates, assuming a 50% increase in the initial cash flow.

Cash flow at IRR	What-if MARR is	Cash flow at MARR	Difference in cash flow	Change in offer price by ship recycling yards of 'x' annual dismantling capacity in million T per year			
				x =1.00	x =1.25	x =1.50	x =2.00
$8,416,170	0.50%	$2,567,490	$5,848,680	$5.85	$4.68	$3.90	$2.92
$8,416,170	1.00%	$2,701,497	$5,714,673	$5.71	$4.57	$3.81	$2.86
$8,416,170	2.00%	$2,981,390	$5,434,780	$5.43	$4.35	$3.62	$2.72
$8,416,170	3.00%	$3,276,766	$5,139,404	$5.14	$4.11	$3.43	$2.57
$8,416,170	4.00%	$3,587,110	$4,829,060	$4.83	$3.86	$3.22	$2.41
$8,416,170	5.00%	$3,911,826	$4,504,344	$4.50	$3.60	$3.00	$2.25
$8,416,170	6.00%	$4,250,247	$4,165,923	$4.17	$3.33	$2.78	$2.08
$8,416,170	7.00%	$4,601,655	$3,814,515	$3.81	$3.05	$2.54	$1.91
$8,416,170	8.00%	$4,965,295	$3,450,875	$3.45	$2.76	$2.30	$1.73

Appendix C: What-if analysis of a 100 TPD plasma gasification plant on ship recycling yards of various dismantling capacities at different discount rates, assuming a 50% increase in the initial cash flow.

Cash flow at IRR	What-if MARR is	Cash flow at MARR	Difference in cash flow	Change in offer price by ship recycling yards of 'x' annual dismantling capacity in million T per year		
				x=1.00	x=0.75	x=0.50
$3,366,468	0.50%	$1,316,661	$2,049,807	$2.05	$2.73	$4.10
$3,366,468	1.00%	$1,385,383	$1,981,085	$1.98	$2.64	$3.96
$3,366,468	2.00%	$1,528,918	$1,837,550	$1.84	$2.45	$3.68
$3,366,468	3.00%	$1,680,393	$1,686,075	$1.69	$2.25	$3.37
$3,366,468	4.00%	$1,839,544	$1,526,924	$1.53	$2.04	$3.05
$3,366,468	5.00%	$2,006,065	$1,360,403	$1.36	$1.81	$2.72
$3,366,468	6.00%	$2,179,614	$1,186,854	$1.19	$1.58	$2.37

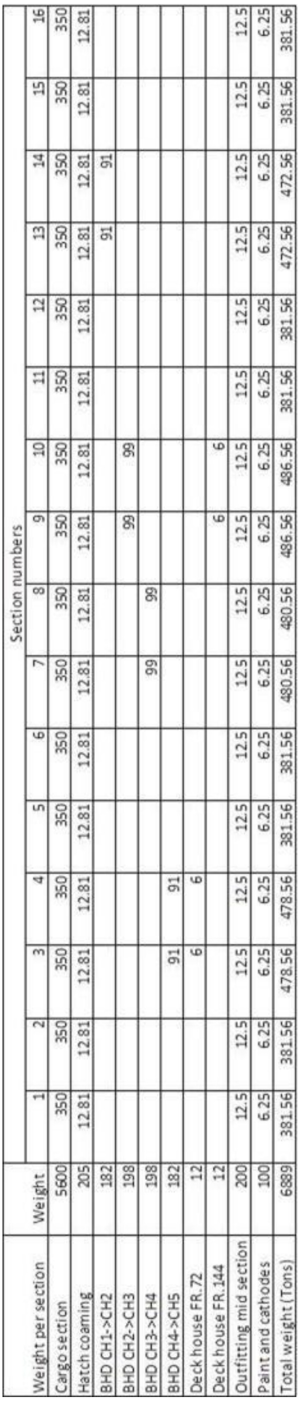
Appendix D: What-if analysis of a 250 TPD plasma gasification plant on ship recycling yards of various dismantling capacities at different discount rates, assuming a 100% increase in the initial cash flow.

Cash flow at IRR	What-if MARR is	Cash flow at MARR	Difference in cash flow	Change in offer price by ship recycling yards of 'x' annual dismantling capacity in million T per year			
				x =1.00	x =1.25	x =1.50	x =2.00
$11,221,560	0.50%	$2,567,490	$8,654,070	$8.65	$6.92	$5.77	$4.33
$11,221,560	1.00%	$2,701,497	$8,520,063	$8.52	$6.82	$5.68	$4.26
$11,221,560	2.00%	$2,981,390	$8,240,170	$8.24	$6.59	$5.49	$4.12
$11,221,560	3.00%	$3,276,766	$7,944,794	$7.94	$6.36	$5.30	$3.97
$11,221,560	4.00%	$3,587,110	$7,634,450	$7.63	$6.11	$5.09	$3.82
$11,221,560	5.00%	$3,911,826	$7,309,734	$7.31	$5.85	$4.87	$3.65
$11,221,560	6.00%	$4,250,247	$6,971,313	$6.97	$5.58	$4.65	$3.49
$11,221,560	7.00%	$4,601,655	$6,619,905	$6.62	$5.30	$4.41	$3.31
$11,221,560	8.00%	$4,965,295	$6,256,265	$6.26	$5.01	$4.17	$3.13

Appendix E: What-if analysis of a 100 TPD plasma gasification plant on ship recycling yards of various dismantling capacities at different discount rates, assuming a 100% increase in the initial cash flow.

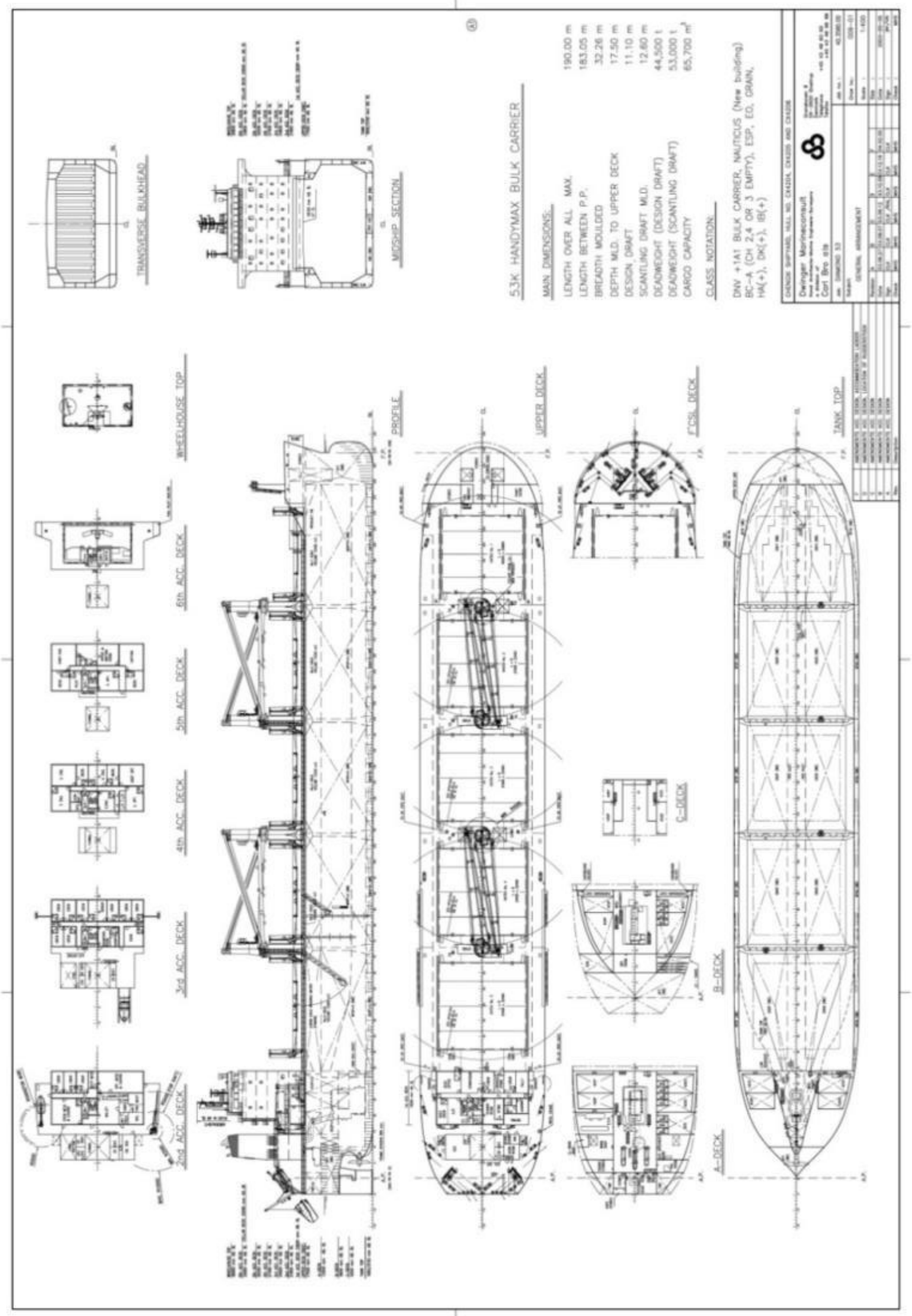
Cash flow at IRR	What-if MARR is	Cash flow at MARR	Difference in cash flow	Change in offer price by ship recycling yards of 'x' annual dismantling capacity in million T per year		
				x=1.00	x=0.75	x=0.50
$4,488,624	0.50%	$1,316,661	$3,171,963	$3.17	$4.23	$6.34
$4,488,624	1.00%	$1,385,383	$3,103,241	$3.10	$4.14	$6.21
$4,488,624	2.00%	$1,528,918	$2,959,706	$2.96	$3.95	$5.92
$4,488,624	3.00%	$1,680,393	$2,808,231	$2.81	$3.74	$5.62
$4,488,624	4.00%	$1,839,544	$2,649,080	$2.65	$3.53	$5.30
$4,488,624	5.00%	$2,006,065	$2,482,559	$2.48	$3.31	$4.97
$4,488,624	6.00%	$2,179,614	$2,309,010	$2.31	$3.08	$4.62

Appendix F: Weight calculation for each dismantling section of the case ship (Berendschot et al., 2015)



Weight per section	Weight	Section numbers															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Cargo section	5600	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350
Hatch coaming	205	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81
BHD CH1->CH2	182													91	91		
BHD CH2->CH3	198									99	99						
BHD CH3->CH4	198							99	99								
BHD CH4->CH5	182			91	91												
Deck house FR.72	12			6	6												
Deck house FR.144	12									6	6						
Outfitting mid section	200	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Paint and cathodes	100	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25	6.25
Total weight (Tons)	6889	381.56	381.56	478.56	478.56	381.56	381.56	480.56	480.56	486.56	486.56	381.56	381.56	472.56	472.56	381.56	381.56

Appendix G: General arrangement of the case ship (CarlBro, 2006)



Appendix H: Accommodation design developed by Fikkert et al. (2013) for offshore platforms

Figure A: 3D model of the referred design (internal module is shown transparent)

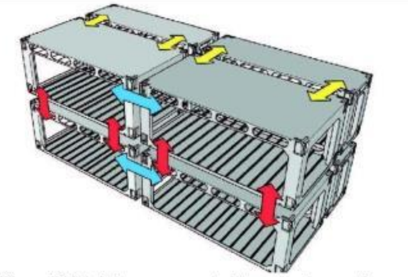


Figure B: Modules are connected to each other on the corners

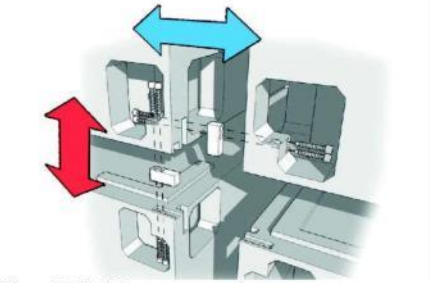


Figure C: Module corner connection

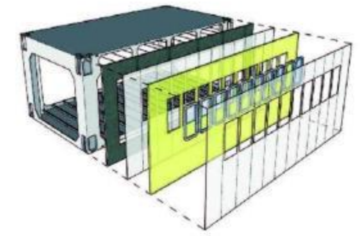


Figure D: Outside wall of a module

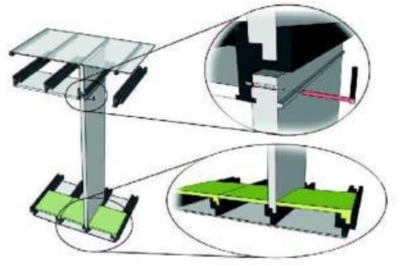


Figure E: System for flooring, walls and ceiling (cross-section)

Figure F: Demountable connections

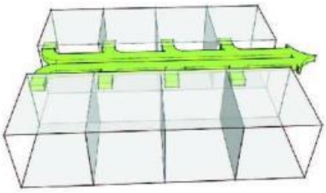


Figure G: Services connecting to the hallway

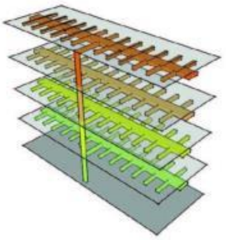


Figure H: Central services connect vertically through a column of staircase modules

References

Abdullah, H. M., Mahboob, M. G., Banu, M. R. & Seker, D. Z. 2013. Monitoring the drastic growth of ship breaking yards in Sitakunda: a threat to the coastal environment of Bangladesh. *Environmental Monitoring and Assessment,* 185**,** 3839-3851. https://doi.org/10.1007/s10661-012-2833-4

Abdulmalek, F. A. & Rajgopal, J. 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of production economics,* 107**,** 223-236. https://doi.org/10.1016/j.ijpe.2006.09.009

ABS 2011. Green Passport- Guide for the Class Notation. Houston: American Bureau of Shipping.

Achinas, S. 2014. Material Flow Analysis (MFA) for Waste Management in Olive Oil Industries sector in South Europe. *Journal of Sustainable Development Studies,* 5.

Adak, S. 2013. EIA and EMP for ship recycling facility near Mundra west port in Kachchh district Gujarat. India: MECON Limited.

Agarwal, R. 01/10/2015 2015. *RE: Second hand market for reusable insulation at Alang recycling yard, India.* Type to Jain, K. P.

Agarwal, R. 03/06/2016 2016a. *RE: Reduction in offer price by new HKC-certified yards in Alang, India.* Type to Jain, K. P.

Agarwal, R. 11/04/2016 2016b. *RE: Second hand market in Alang recycling yard, India.* Type to Jain, K. P.

Ahuja, M. 2012. *Driving Sustainable Ship Recycling: A Case Study of the Container Shipping Industry.* MSc., Faculty of Social Sciences and Technology Management, Department of Industrial Economics and Technology Management, NTNU - Norwegian University of Science and Technology.

Ahuja, M., Fet, A. M. & Aspen, D. M. 2011. An overview of the end-of-life treatment of ships. *Innovation in Global Maritime Production 2020.* Trondheim: Norwegian University of Science and Technology (NTNU).

Alcaidea, J. I., Piniella, F. & Rodríguez-Díaza, E. 2016. The “Mirror Flags”: Ship registration in globalised ship breaking industry. *Transportation Research Part D: Transport and Environment,* 48**,** 378-392. http://dx.doi.org/10.1016/j.trd.2016.08.020

Alkaner, S., Das, P. K., Smith, D. L. & Dilok, P. 2006. Comparative Analysis of Ship Production and Ship Dismantling. *International Conference on Dismantling of Obsolete Vessels.* Glasgow, UK.

Allen, F. W., Halloran, P. A., Leith, A. H. & Lindsay, M. C. 2009. Using material flow analysis for sustainable materials management. *Journal of Industrial Ecology,* 13**,** 662-665. http://dx.doi.org/10.1111/j.1530-9290.2009.00168.x

Almeida, E., Diamantino, T. C. & de Sousa, O. 2007. Marine paints: The particular case of antifouling paints. *Progress in Organic Coatings,* 59**,** 2-20. http://dx.doi.org/10.1016/j.porgcoat.2007.01.017

Andersen, A. B., Endresen, Ø., Hall, S., Jose, P., Kattan, R., Orrick, P., Rydock, A. & Sverud, T. 2001. Technological and Economic Feasibility Study of Ship Scrapping in Europe. *Report No. 2000-3527*. Hovik, Norway: DNV.

Andersen, A. B., Røstad, A. & Bjørnbom, E. 1999. Decommissioning of ships environmental protection and ship demolition practices. *Report No. 99-3065*. Hovik, Norway: DNV.

Ardente, F., Calero Pastor, M., Mathieux, F. & Talens Peiró, L. 2015. Analysis of end-of-life treatments of commercial refrigerating appliances: Bridging product and waste policies. *Resources, Conservation and Recycling,* 101**,** 42-52. https://doi.org/10.1016/j.resconrec.2015.05.005

Arena, U. 2012. Process and technological aspects of municipal solid waste gasification. A review. *Waste Management,* 32**,** 625-639. http://dx.doi.org/10.1016/j.wasman.2011.09.025

Arena, U. & Di Gregorio, F. 2014. A waste management planning based on substance flow analysis. *Resources, Conservation and Recycling,* 85**,** 54-66. http://dx.doi.org/10.1016/j.resconrec.2013.05.008

Asariotis, R., Benamara, H., Finkenbrink, H., Hoffmann, J., Jaimurzina, A., Premti, A., Valentine, V. & Youssef, F. 2012. Review of Maritime Transport. New York and Geneva: UNCTAD.

Baas, L. W. 1995. Cleaner production: beyond projects. *Journal of Cleaner Production,* 3**,** 55-59. http://dx.doi.org/10.1016/0959-6526(95)00042-D

Ballard, G. & Howell, G. 1994. Implementing lean construction: stabilizing work flow. *Lean construction***,** 101-110.

Barrass, B. & Derrett, C. D. 2011. *Ship stability for masters and mates,* Butterworth-Heinemann. ISBN: 9780123741547

Barrass, C. B. 2004. *Ship design and performance for masters and mates,* Amsterdam, Elsevier Butterworth-Heinemann. ISBN: 9780750660006

BC. 2011a. *The Basel Convention Ban Amendment* [Online]. Available: http://www.basel.int/Implementation/LegalMatters/BanAmendment/Overview/tabid/1484/Default.aspx [Accessed 13.09.2016].

BC. 2011b. *Basel Convention Overview* [Online]. Available: http://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx [Accessed 13.09.2016].

Berendschot, R., Boonstra, R., Geldermans, D. & Mooren, M. 2015. Design for Recycling: Technical implementations to improve the process of ship recycling. *In:* Jain, K. P. (ed.) *BEP Report.* TU Delft.

Bertram, V. & Schneekluth, H. 1998. *Ship design for efficiency and economy,* Butterworth-Heinemann. ISBN: 9780080972749

Bertram, V. & Thiart, G. D. 2005. Simulation-based ship design. *Oceans 2005 - Europe.*

Bhattacharjee, S. 2009. From Basel to Hong Kong: international environmental regulation of ship-recycling takes one step forward and two steps back. *Trade L. & Dev.,* 1**,** 193. https://ssrn.com/abstract=1760459

BIMCO. 2016. *Demolishcon* [Online]. Available: https://www.bimco.org/Chartering/Clauses_and_Documents/Documents/Sale_and_Purchase/DEMOLISHCON.aspx [Accessed 08.09.2016].

Binder, C. R. & Mosler, H.-J. 2007. Waste-resource flows of short-lived goods in households of Santiago de Cuba. *Resources, Conservation and Recycling,* 51**,** 265-283. https://doi.org/10.1016/j.resconrec.2006.04.001

Blankestijn, T. P. 2012. *RE: MSc Thesis Driving Sustainable Ship Recycling A Case Study of the Container Shipping Industry.* Type to Ahuja, M.

Bohnes, H. & Richter, B. 1997. Cathodic Protection of Ships. *In:* Von Baeckmann, W., Schwenk, W. & Prinz, W. (eds.) *Handbook of Cathodic Corrosion Protection.* Houston: Gulf Professional Publishing. ISBN: 9780884150565

Bois, R. d. 2012. Ship-breaking.com 2011. *In:* Bonnemains, J. & Bossard, C. (eds.) *Bulletins of information and analysis on ship demolition.* Robin des Bois.

Bois, R. d. 2013. Ship-breaking.com 2012. *In:* Bonnemains, J. & Bossard, C. (eds.) *Bulletins of information and analysis on ship demolition.* Robin des Bois.

Bois, R. d. 2014. Ship-Breaking 2013. *In:* Bonnemains, J. & Bossard, C. (eds.) *Bulletins of information and analysis on ship demolition.* Robin des Bois.

Bois, R. d. 2015. Ship-Breaking 2014. *In:* Bonnemains, J. & Bossard, C. (eds.) *Bulletins of information and analysis on ship demolition.* Robin des Bois.

Bonilla, S. H., Almeida, C. M. V. B., Giannetti, B. F. & Huisingh, D. 2010. The roles of cleaner production in the sustainable development of modern societies: an introduction to this special issue. *Journal of Cleaner Production,* 18**,** 1-5. http://dx.doi.org/10.1016/j.jclepro.2009.09.001

Bosmans, A., Vanderreydt, I., Geysen, D. & Helsen, L. 2013. The crucial role of Waste-to-Energy technologies in enhanced landfill mining: a technology review. *Journal of Cleaner Production,* 55**,** 10-23. http://dx.doi.org/10.1016/j.jclepro.2012.05.032

Brandao de Souza, L. 2009. Trends and approaches in lean healthcare. *Leadership in Health Services,* 22**,** 121-139. http://dx.doi.org/10.1108/17511870910953788

Brunner, P. & Rechberger, H. 2004. *Practical handbook of material flow analysis,* New York, Lewis Publisher. ISBN: 9781566706049

Brunner, P. H., Morf, L. & Rechberger, H. 2004. VI.3 Thermal waste treatment—a necessary element for sustainable waste management. *In:* Twardowska, I., Allen, H. E., Kettrup, A. A. F. & Lacy, W. J. (eds.) *Solid Waste: Assessment, Monitoring and Remediation (Waste Management Series).* Amsterdam, The Netherlands: Elsevier. ISBN: 9780080443218 http://dx.doi.org/10.1016/S0713-2743(04)80033-3

Bugallo, P. M. B., Stupak, A., Andrade, L. C. & López, R. T. 2012. Material Flow Analysis in a cooked mussel processing industry. *Journal of Food Engineering,* 113**,** 100-117. https://doi.org/10.1016/j.jfoodeng.2012.05.014

Buxton, I. L. 1976. Engineering economics and ship design. *In:* Association, B. S. R. (ed.). Wallend Research Station, Wallsend, England: Transportation Research Information Services.

Buxton, I. L. 1991. The market for ship demolition. *Maritime Policy & Management,* 18**,** 105-112. https://doi.org/10.1080/03088839100000034

Byun, Y., Chung, J., Cho, M. & Hwang, S.-M. 2012. Thermal Plasma Gasification of Municipal Solid Waste (MSW). *In:* Yun, Y. (ed.) *Gasification for Practical Applications.* Croatia: INTECH Open Access Publisher. ISBN: 9789535108184 https://doi.org/10.5772/48537

Cagno, E., Trucco, P. & Tardini, L. 2005. Cleaner production and profitability: analysis of 134 industrial pollution prevention (P2) project reports. *Journal of Cleaner Production,* 13**,** 593-605. http://dx.doi.org/10.1016/j.jclepro.2003.12.025

Cahill, M. & Kosicki, G. 2000. Exploring Economic Models Using Excel. *Southern Economic Journal,* 66**,** 770-792. https://doi.org/10.2307/1061439

Cameron-Dow, L.-L. 2013. Challenges Posed by the Entry into Force Requirements of the Hong Kong Convention: Desperately Seeking a White Rabbit to Lead us into Wonderland. *In:* Bellefontaine, N., Olcer, A. & Hilderbrand, L. (eds.) *International Conference on Ship Recycling.* World Maritime University, Malmo, Sweden: WMU Publications.

CarlBro. 2006. *Stability Information Manual* [Online]. Available: http://bit.ly/1Yrvs7E [Accessed 30.07.2015].

CDA. 2015. *Copper-Nickel Alloys in Shipbuilding and Repair* [Online]. Copper Development Association Inc. Available: http://bit.ly/1NNbJI6 [Accessed 30.07.2015].

Cencic, O. & Rechberger, H. 2008. Material flow analysis with software STAN. *Journal of Environmental Engineering and Management,* 18**,** 3.

Chang, Y.-C., Wang, N. & Durak, O. S. 2010. Ship recycling and marine pollution. *Marine pollution bulletin,* 60**,** 1390-1396. https://doi.org/10.1016/j.marpolbul.2010.05.021

Choi, J.-K., Kelley, D., Murphy, S. & Thangamani, D. 2016. Economic and environmental perspectives of end-of-life ship management. *Resources, Conservation and Recycling,* 107**,** 82-91. https://doi.org/10.1016/j.resconrec.2015.12.007

Clark, B. & Rogoff, M. 2010. Economic feasibility of a plasma arc gasification plant, city of Marion, Iowa. *18th Annual North American Waste-to-Energy Conference, NAWTEC18.* Orlando, Florida, USA: ASME.

Clarksons. 2016. *When the Going Gets Tough...* [Online]. Wordpress.com: Clarksons Research. Available: https://clarksonsresearch.wordpress.com/2016/03/04/when-the-going-gets-tough/ [Accessed 22.08.2016].

ClassNK. 2017. *Ship Recycling Convention (the Hong Kong Convention)* [Online]. Available: http://www.classnk.or.jp/hp/en/activities/statutory/shiprecycle/ [Accessed 27.02.2017].

CMP. 2015. *Data Sheets* [Online]. Available: http://bit.ly/1YrvAE0 [Accessed 30.07.2015].

Crang, M., Hughes, A., Gregson, N., Norris, L. & Ahamed, F. 2013. Rethinking governance and value in commodity chains through global recycling networks.

Transactions of the Institute of British Geographers, 38**,** 12-24. https://doi.org/10.1111/j.1475-5661.2012.00515.x

Cyranoski, D. 2006. Waste management: One man's trash. *Nature,* 444**,** 262-263. https://doi.org/10.1038/444262a

Danthurebandara, M., Van Passel, S., Vanderreydt, I. & Van Acker, K. 2015. Environmental and economic performance of plasma gasification in Enhanced Landfill Mining. *Waste Management,* 45**,** 458-467. http://dx.doi.org/10.1016/j.wasman.2015.06.022

De Brito, M. P., Van der Laan, E. & Irion, B. D. 2007. Extended producer responsibility in the aviation sector. *ERIM Report Series Reference No. ERS-2007-025-LIS.*

DEFRA 2007. Overview of ship recycling in the UK: Guidance. London: Department for Environment, Food and Rural Affairs.

Demaria, F. 2010. Shipbreaking at Alang–Sosiya (India): an ecological distribution conflict. *Ecological Economics,* 70**,** 250-260. https://doi.org/10.1016/j.ecolecon.2010.09.006

Detty, R. B. & Yingling, J. C. 2000. Quantifying benefits of conversion to lean manufacturing with discrete event simulation: a case study. *International Journal of Production Research,* 38**,** 429-445. http://dx.doi.org/10.1080/002075400189509

Dev, A. K. 2010. Various aspects of sound ship recycling in south Asia: a compromise not a confrontation! *The International Conference on Marine Technology MARTEC 2010.* BUET, Dhaka, Bangladesh.

Devault, D. A., Beilvert, B. & Winterton, P. 2016. Ship breaking or scuttling? A review of environmental, economic and forensic issues for decision support. *Environmental Science and Pollution Research***,** 1-34. https://doi.org/10.1007/s11356-016-6925-5

Dieleman, H. 2007. Cleaner production and innovation theory. Social experiments as a new model to engage in cleaner production. *Rev. Int. Contam. Ambient,* 23**,** 79-94. http://ref.scielo.org/zwdn7b

Digman, B., Joo, H. S. & Kim, D.-S. 2009. Recent progress in gasification/pyrolysis technologies for biomass conversion to energy. *Environmental Progress & Sustainable Energy,* 28**,** 47-51. https://doi.org/10.1002/ep.10336

DNV 2011. Stability documentation for approval. *Classification notes no. 20.1.* Norway: DNV.

DNVGL 2015. Rules for Classification and Construction: Ship Technology. *Part 1: Seagoing Ships, Chapter 2: Machinery Installations, Section 11: Piping Systems, Valves and Pumps.* Hamburg: DNVGL SE.

Dodge, E. 2008. Plasma Gasification of Waste: Clean Production of Renewable Fuels through the Vaporization of Garbage. Cornell University – Johnson Graduate School of Management.

Dodić, S. N., Vučurović, D. G., Popov, S. D., Dodić, J. M. & Zavargo, Z. Z. 2010. Concept of cleaner production in Vojvodina. *Renewable and Sustainable Energy Reviews,* 14**,** 1629-1634. https://doi.org/10.1016/j.rser.2010.02.004

Dorfman, M., White, A., Becker, M. & Jackson, T. 1993. Profiting from Pollution Prevention. *In:* Jackson, T. (ed.) *Cleaner Production Strategies: Developing*

Preventive Environmental Management in the Industrial Economy. London: Lewis Publishers. ISBN: 9780873718844

DSA. 2016. *Denmark to ratify the Hong Kong Convention for safe recycling of vessels* [Online]. Danish Shipowner's Association. Available: https://www.shipowners.dk/en/presse/nyheder/denmark-to-ratify-the-hong-kong-convention-for-safe-recycling-of-vessels/ [Accessed 14.09.2016].

Ducharme, C. 2010. *Technical and economic analysis of Plasma-assisted Waste-to-Energy processes.* M.Sc., Department of Earth and Environmental Engineering, Fu Foundation of Engineering and Applied Science, Columbia University.

Durham, E., Hewitt, A., Bell, R. & Russell, S. 2015. 7 - Technical design for recycling of clothing A2 - Blackburn, Richard. *Sustainable Apparel.* Woodhead Publishing. ISBN: 9781782423393 http://dx.doi.org/10.1016/B978-1-78242-339-3.00007-8

EC 2004. Oil Tanker Phase Out and the Ship Scrapping Industry: A study on the implications of the accelerated phase out scheme of single hull tankers. COWI for European Commission.

EC 2007. Green Papaer on Better Ship Dismantling. Brussels: European Commission.

EC 2016. European List of ship recycling facilities. Brussels: European Commission.

El-Haggar, S. M. 2007. Chapter 2 - Cleaner Production. *Sustainable Industrial Design and Waste Management.* Oxford: Academic Press. ISBN: 9780123736239 http://dx.doi.org/10.1016/B978-012373623-9/50004-6

Engels, U. D. 2013. *European Ship Recycling Regulation: Entry-Into-Force Implications of the Hong Kong Convention,* Heidelberg, Springer Science and Business Media. ISBN: 9783642355974

EU 2013. Regulation (EU) No 1257/2013 of the European Parliament and of the council of 20 November 2013 on ship recycling and amending Regulation (EC) No 1013/2006 and Directive 2009/16/EC. *Official Journal of the European Union,* 56.

EU 2016. Requirements and procedure for inclusion of facilities located in third countries in the European List of ship recycling facilities (Technical guidance note under Regulation (EU) No 1257/2013 on ship recycling). *Official Journal of the European Union,* 59.

Evans, J. 1989. Replacement, obsolescence and modifications of ships. *Maritime Policy & Management,* 16**,** 223-231. http://dx.doi.org/10.1080/03088838900000061

Eyres, D. J. 2007. *Ship construction,* Oxford, Butterworth-Heinemann. ISBN: 9780080468235

Fabry, F., Rehmet, C., Rohani, V. & Fulcheri, L. 2013. Waste Gasification by Thermal Plasma: A Review. *Waste and Biomass Valorization,* 4**,** 421-439. https://doi.org/10.1007/s12649-013-9201-7

Ferrão, P. & Amaral, J. 2006. Design for recycling in the automobile industry: New approaches and new tools. *Journal of Engineering Design,* 17**,** 447-462. https://doi.org/10.1080/09544820600648039

Ferrão, P., Nazareth, P. & Amaral, J. 2006. Strategies for meeting EU end-of-life vehicle reuse/recovery targets. *Journal of Industrial Ecology,* 10**,** 77-93. https://doi.org/10.1162/jiec.2006.10.4.77

Fikkert, R. C., Otheguy, M. E. & Durmisevic, E. 2013. Design for Disassembly as a Method to Improve the Sustainability of Offshore Accommodations. *KOMtech Technology Review***,** 91-103.

Fränzle, S., Markert, B. & Wünschmann, S. 2012. *Introduction to Environmental Engineering,* Weinheim, Germany, John Wiley & Sons. ISBN: 9783527329816

Fresner, J. 1998. Cleaner production as a means for effective environmental management. *Journal of cleaner production,* 6**,** 171-179. https://doi.org/10.1016/S0959-6526(98)00002-X

Gaspar, H., Ross, A., Rhodes, D. & Erikstad, S. 2012. Handling complexity aspects in conceptual ship design. *International Maritime Design Conference, Glasgow, UK.*

Gerrard, J. & Kandlikar, M. 2007. Is European end-of-life vehicle legislation living up to expectations? Assessing the impact of the ELV Directive on 'green' innovation and vehicle recovery. *Journal of Cleaner Production,* 15**,** 17-27. https://doi.org/10.1016/j.jclepro.2005.06.004

Glavič, P. & Lukman, R. 2007. Review of sustainability terms and their definitions. *Journal of cleaner production,* 15**,** 1875-1885. https://doi.org/10.1016/j.jclepro.2006.12.006

GMS. 2017. *Market sentiments for end-of-life ships* [Online]. Available: http://www.gmsinc.net/gms_new/index.php/web [Accessed 10.03.2017].

Gomez, E., Rani, D. A., Cheeseman, C. R., Deegan, D., Wise, M. & Boccaccini, A. R. 2009. Thermal plasma technology for the treatment of wastes: A critical review. *Journal of Hazardous Materials,* 161**,** 614-626. http://dx.doi.org/10.1016/j.jhazmat.2008.04.017

Gould, O. & Colwill, J. 2015. A framework for material flow assessment in manufacturing systems. *Journal of Industrial and Production Engineering,* 32**,** 55-66. http://dx.doi.org/10.1080/21681015.2014.1000403

Graham-Rowe, D. 2004. Ship scrapping: Breaking up is hard to do. *Nature,* 429**,** 800-802. http://dx.doi.org/10.1038/429800a

Green4sea. 2017. *Turkey ratifies Hong Kong Convention* [Online]. Available: http://www.green4sea.com/turkey-ratifies-hong-kong-convention/ [Accessed 02.05.2017].

Gregson, N., Crang, M., Ahamed, F. U., Akter, N., Ferdous, R., Foisal, S. & Hudson, R. 2012. Territorial Agglomeration and Industrial Symbiosis: Sitakunda ‐ Bhatiary, Bangladesh, as a Secondary Processing Complex. *Economic Geography,* 88**,** 37-58. http://dx.doi.org/10.1111/j.1944-8287.2011.01138.x

Grünberg, T. 2003. A review of improvement methods in manufacturing operations. *Work study,* 52**,** 89-93. http://dx.doi.org/10.1108/00438020310462890

Gupta, S. & Starr, M. 2014. *Production and Operations Management Systems,* Boca Raton, Florida, CRC Press: Taylor and Francis Group. ISBN: 9781466507333

Hagemann, H. 1990. Internal rate of return. *In:* Eatwell, J., Milgate, M. & Newman, P. (eds.) *Capital Theory.* London: Palgrave Macmillan UK. ISBN: 9780333495476 https://doi.org/10.1007/978-1-349-20861-6_16

Hartman, J. C. & Schafrick, I. C. 2004. The relevant internal rate of return. *The Engineering Economist,* 49**,** 139-158. https://doi.org/10.1080/00137910490453419

Hernandez-Matias, J.-C., Vizán, A., Hidalgo, A. & Ríos, J. 2006. Evaluation of techniques for manufacturing process analysis. *Journal of Intelligent Manufacturing,* 17**,** 571-583. http://dx.doi.org/10.1007/s10845-006-0025-1

Hernandez-Matias, J., Vizan, A., Perez-Garcia, J. & Rios, J. 2008. An integrated modelling framework to support manufacturing system diagnosis for continuous improvement. *Robotics and computer-integrated manufacturing,* 24**,** 187-199. https://doi.org/10.1016/j.rcim.2006.10.003

Hess, R. W., Rushworth, D., Hynes, M. V. & Peters, J. E. 2001. Disposal options for ships. DTIC Document.

Hiremath, A. M., Pandey, S. K. & Asolekar, S. R. 2016. Development of ship-specific recycling plan to improve health safety and environment in ship recycling yards. *Journal of Cleaner Production,* 116**,** 279-298. http://dx.doi.org/10.1016/j.jclepro.2016.01.006

Hiremath, A. M., Tilwankar, A. K. & Asolekar, S. R. 2015. Significant steps in ship recycling vis-a-vis wastes generated in a cluster of yards in Alang: a case study. *Journal of Cleaner Production,* 87**,** 520-532. https://doi.org/10.1016/j.jclepro.2014.09.031

Hougee, M. 2013. *Shades of green in the shiprecycling industry: An assessment of corporate end-of-life vessel policies and practices.* M.Sc., Environmental Policy Group, Department of Social Sciences, Wageningen University.

Huang, C.-L., Vause, J., Ma, H.-W. & Yu, C.-P. 2012. Using material/substance flow analysis to support sustainable development assessment: A literature review and outlook. *Resources, Conservation and Recycling,* 68**,** 104-116. http://dx.doi.org/10.1016/j.resconrec.2012.08.012

IACS 2011. Classification Societies - What, Why and How? UK: International Association of Classification Societies.

IACS 2014. Requirements concerning mooring, anchoring and towing. *In:* IACS (ed.).

Imaduddin. 2012. *Ship-breaking and steel sectors: DGI & IIR all set to check tax evasion* [Online]. Business Recorder. Available: http://bit.ly/1PLVFfv [Accessed 23.11.2015].

IMO 2003. IMO guidelines on ship recycling. *Resolution A.962(23).* International Maritime Organization.

IMO. Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, 2009. International Conference on the Safe and Environmentally Sound Recycling of Ships, 2009 Hong Kong. IMO.

IMO 2011a. Guidelines for the development of the inventory of hazardous materials. *In:* IMO (ed.) *Annex 3 Resolution MEPC.197(62).*

IMO 2011b. Guidelines for the development of the ship recycling plan. *In:* IMO (ed.) *Annex 2 Resolution MEPC.196(62).*

IMO 2012a. Guidelines for safe and environmentally sound ship recycling. *In:* IMO (ed.) *Annex 4 Resolution MEPC.210(63).*

IMO 2012b. Guidelines for the authorization of ship recycling facilities. *In:* IMO (ed.) *Annex 5 Resolution MEPC.211(63).*

IMO 2012c. Guidelines for the inspection of ships under the Hong Kong convention. *In:* IMO (ed.) *Resolution MEPC.223(64).*

IMO 2012d. Guidelines for the survey and certification of ships under the Hong Kong convention. *In:* IMO (ed.) *Resolution MEPC.222(64).*

IMO. 2015. *Recycling of ships* [Online]. Available: http://bit.ly/1XbPCW0 [Accessed 30.07.2015].

IMO. 2016. *Accelerated phase-out for single-hull tankers* [Online]. IMO. Available: http://www.imo.org/en/OurWork/Safety/Regulations/Pages/OilTankers.aspx [Accessed 09 Aug 2016].

Iqbal, K. M. J. & Heidegger, P. 2013. Pakistan Shipbreaking Outlook: The Way Forward for a Green Ship Recycling Industry – Environmental, Health and Safety Conditions. Brussels/Islamabad: Sustainable Development Policy Institute and the NGO Shipbreaking Platform.

Jackson, T. 2002. Industrial ecology and cleaner production. *In:* Ayres, R. U. & Ayres, L. W. (eds.) *A handbook of industrial ecology.* Cheltenham, UK: Edward Elgar Publishing Ltd. ISBN: 9781840645064

Jacobsen, N. B. 2006. Industrial Symbiosis in Kalundborg, Denmark: A Quantitative Assessment of Economic and Environmental Aspects. *Journal of Industrial Ecology,* 10**,** 239-255. https://doi.org/10.1162/108819806775545411

Jain, K. P. & Pruyn, J. Economic Impact Assessment of Using a Plasma Gasification Plant on a Large Ship Recycling Yard. *In:* Clarke, W. P., Cossu, R., Diaz, L. F., Liu, J., Matsuto, T., Nelles, M. & Stegmann, R., eds. Venice 2016 - Sixth International Symposium on Energy from Biomass and Waste, 2016 Venice. Padova, Italy: CISA Publisher.

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2013. Critical Analysis of the Hong Kong International Convention on Ship Recycling. *In:* Vaninsky, A., Semonov, E. & Bolitin, A., eds. World Academy of Science, Engineering and Technology Conference, 2013 Dubai. Dubai: WASET, 684-692.

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2014. Influence of ship design on ship recycling. *In:* Soares, C. G. & Santos, T. A., eds. 2nd International Conference on Maritime Technology and Engineering (MARTECH 2014), 2014 Lisbon, Portugal. London, U.K.: CRC Press - Taylor and Francis Group, 269-276. http://doi.org/10.1201/b17494-37

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2016. Improving ship design process to enhance ship recycling. *In:* Soares, C. G. & Santos, T. A., eds. 3rd International Conference on Maritime Technology and Engineering (MARTECH 2016), 2016a Lisbon, Portugal. London, U.K.: CRC Press - Taylor and Francis Group, 663-671. https://doi.org/10.1201/b21890-86

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2016b. Quantitative assessment of material composition of end-of-life ships using onboard documentation. *Resources, Conservation and Recycling,* 107**,** 1-9. http://dx.doi.org/10.1016/j.resconrec.2015.11.017

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2017. Material Flow Analysis (MFA) as a tool to improve ship recycling. *Ocean Engineering,* 130**,** 674-683. https://doi.org/10.1016/j.oceaneng.2016.11.036

Jeff, S. & Gregory, A. 2001. Management of end-of life vehicles (ELVs) in the US. *A report of the center for sustainable systems no. CSS01-01*.

Jones, D. & Mitchell, A. 2006. Lean thinking for the NHS. *London: NHS confederation*.

Kagkarakis, N. D., Merikas, A. G. & Merika, A. 2016. Modelling and forecasting the demolition market in shipping. *Maritime Policy & Management***,** 1-15. http://dx.doi.org/10.1080/03088839.2016.1185181

Kanari, N., Pineau, J. L. & Shallari, S. 2003. End-of-Life Vehicle Recycling in the European Union. *JOM,* 55**,** 15-19. http://dx.doi.org/10.1007/s11837-003-0098-7

King, P. L. 2009. *Lean for the process industries - Dealing with complexity,* New York, Taylor and Francis Group. ISBN: 9781420078510

Kjaerheim, G. 2005. Cleaner production and sustainability. *Journal of cleaner production,* 13**,** 329-339. https://doi.org/10.1016/S0959-6526(03)00119-7

Kliopova, I. & Staniskis, J. K. 2006. The evaluation of Cleaner Production performance in Lithuanian industries. *Journal of cleaner production,* 14**,** 1561-1575. https://doi.org/10.1016/j.jclepro.2005.04.017

Knapp, S., Kumar, S. N. & Remijn, A. B. 2008. Econometric analysis of the ship demolition market. *Marine Policy,* 32**,** 1023-1036. http://dx.doi.org/10.1016/j.marpol.2008.02.004

Koga, T., Matsubara, M. & Aoyama, K. Disassembling System of Large Scaled Structure Considering Safety, Environmental Impact, and Economic Efficiency. ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2008. American Society of Mechanical Engineers, 279-288.

Koranda, C., Chong, W. K., Kim, C., Chou, J.-S. & Kim, C. 2012. An investigation of the applicability of sustainability and lean concepts to small construction projects. *KSCE Journal of Civil Engineering,* 16**,** 699-707. http://dx.doi.org/10.1007/s12205-012-1460-5

Krishna, G. 2010. *Shipbreakers face raid by Economic Intelligence Wing* [Online]. IMO WATCH. Available: http://bit.ly/1PX0ukK [Accessed 23.11.2015].

Krishnaraj, S. 2015. *Safe and effective ship recycling in India by introducing the concept of Demolition Shipbroking and the implementation of a Demolition Brokers' checklist.* MSc., Netherlands Maritime University.

Kumar, R. 2009. Ship Dismantling-A Status Report on South Asia. *Euroconsult Mott MacDonald and WWF-India*.

Kuo, T. C. 2010. The construction of a collaborative-design platform to support waste electrical and electronic equipment recycling. *Robotics and Computer-Integrated Manufacturing,* 26**,** 100-108. http://dx.doi.org/10.1016/j.rcim.2009.05.004

Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C. & Wiktorsson, M. 2015. Waste flow mapping to improve sustainability of waste management: a case study approach. *Journal of Cleaner Production,* 98**,** 304-315. https://doi.org/10.1016/j.jclepro.2014.06.076

Lamb, T. 2003. *Ship Design and Construction*, Society of Naval Architects and Marine Engineers. ISBN: 9780939773411

Larderel, J. A. d. 2002. Cleaner Production Seventh International High-level Seminar Prague. *Industry and Environment,* 25**,** 5.

Lee, K. F. 2001. Sustainable tourism destinations: the importance of cleaner production. *Journal of Cleaner Production,* 9**,** 313-323. https://doi.org/10.1016/S0959-6526(00)00071-8

Lee, M. A. 2012. *Korean Perspectives on Ship Recycling.* M.Sc., IIIEE, Lund University.

Li, J., Liu, K., Yan, S., Li, Y. & Han, D. 2016a. Application of thermal plasma technology for the treatment of solid wastes in China: An overview. *Waste Management,* 58**,** 260-269. http://dx.doi.org/10.1016/j.wasman.2016.06.011

Li, Y., Zhang, X., Ding, G. & Feng, Z. 2016b. Developing a quantitative construction waste estimation model for building construction projects. *Resources, Conservation and Recycling,* 106**,** 9-20. http://dx.doi.org/10.1016/j.resconrec.2015.11.001

LloydsRegister 2011. Classification news. *Statutory alert Asbestos on board ships – contravention of SOLAS requirements* London.

Lopes Silva, D. A., Delai, I., Soares de Castro, M. A. & Ometto, A. R. 2013. Quality tools applied to Cleaner Production programs: a first approach toward a new methodology. *Journal of Cleaner Production,* 47**,** 174-187. http://dx.doi.org/10.1016/j.jclepro.2012.10.026

López-Gamero, M. D., Molina-Azorín, J. F. & Claver-Cortés, E. 2010. The potential of environmental regulation to change managerial perception, environmental management, competitiveness and financial performance. *Journal of Cleaner Production,* 18**,** 963-974. http://dx.doi.org/10.1016/j.jclepro.2010.02.015

LR. 2011. Ship recycling: Practice and regulation today. Available: http://www.lr.org/Images/ShipRecycling_040711_tcm155-223320.pdf.

LR. 2017. *Lloyd's Register verified ship recycling facilities* [Online]. Available: http://www.lr.org/en/services/ship-recycling/verified-ship-recycling-facilities.aspx [Accessed 27.02.2017].

Marisec 2001. Industry Code of Practice on Ship Recycling. London: International Chamber of Shipping.

Mat Saman, M. Z. & Blount, G. N. 2006. End of life vehicles recovery: process description, its impact and direction of research. *Jurnal Mekanikal***,** 40-52.

Mathieux, F. & Brissaud, D. 2010. End-of-life product-specific material flow analysis. Application to aluminum coming from end-of-life commercial vehicles in Europe. *Resources, Conservation and Recycling,* 55**,** 92-105. https://doi.org/10.1016/j.resconrec.2010.07.006

Mayyas, A., Qattawi, A., Omar, M. & Shan, D. 2012. Design for sustainability in automotive industry: A comprehensive review. *Renewable and Sustainable Energy Reviews,* 16**,** 1845-1862. http://dx.doi.org/10.1016/j.rser.2012.01.012

Mazzocato, P., Savage, C., Brommels, M., Aronsson, H. & Thor, J. 2010. Lean thinking in healthcare: a realist review of the literature. *Quality and Safety in Health Care,* 19**,** 376-382. https://doi.org/10.1136/qshc.2009.037986

McKenna, S. A., Kurt, R. E. & Turan, O. 2012. A methodology for a 'design for ship recycling'. *Royal Institution of Naval Architects - International Conference on the Environmentally Friendly Ship.* London: RINA.

Meier, I. & Tarhan, V. 2007. Corporate Investment Decision Practices and the Hurdle Rate Premium Puzzle. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.960161

Melton, T. 2005. The benefits of lean manufacturing: what lean thinking has to offer the process industries. *Chemical Engineering Research and Design,* 83**,** 662-673. https://doi.org/10.1205/cherd.04351

Meyers, F. E. & Stephens, M. P. 2005. *Manufacturing facilities design and material handling,* USA, Prentice Hall. ISBN: 9780131125353

Mikelis, N. 2012. The Emergence of an International Regulatory regime for the Ship Recycling Industry. *Lloyd's Maritime Academy Sale and Purchase Conference.* London.

Mikelis, N. 2013a. An analysis of the European Regulation on ship recycling. *BIMCO Bulletin no. 6/2013.* BIMCO.

Mikelis, N. 2013b. Ship Recycling Markets and the Impact of the Hong Kong Convention. *In:* Bellefontaine, N., Olcer, A. & Hilderbrand, L. (eds.) *International Conference on Ship Recycling.* World Maritime University, Malmo, Sweden: WMU Publications.

Misra, P. & Mukherjee, A. 2009. *Ship Recycling: A Handbook for Mariners,* New Delhi, Narosa Publishing House. ISBN: 9788173199219

Mizanur Rahman, S. M. & Mayer, A. L. 2015. How social ties influence metal resource flows in the Bangladesh ship recycling industry. *Resources, Conservation and Recycling,* 104**,** 254-264. http://dx.doi.org/10.1016/j.resconrec.2015.07.022

Moen, A. E. 2008. Breaking Basel: The elements of the Basel Convention and its application to toxic ships. *Marine Policy,* 32**,** 1053-1062. https://doi.org/10.1016/j.marpol.2008.03.002

Molland, A. F. 2011. *The maritime engineering reference book: a guide to ship design, construction and operation,* Elsevier. ISBN: 9780750689878

Mountouris, A., Voutsas, E. & Tassios, D. 2006. Solid waste plasma gasification: Equilibrium model development and exergy analysis. *Energy Conversion and Management,* 47**,** 1723-1737. http://dx.doi.org/10.1016/j.enconman.2005.10.015

Mudgal, S., Benito, P., Kong, M. A., Dias, D. & Carreno, A. M. 2010. The feasibility of a list of green and safe ship dismantling facilities and a list of ships likely to go for dismantling. Bio Intelligence Service for European Commission.

Murdoch, E. 2012. The Master's Guide to Ships' Piping. London: Standard Club.

Nilson, L., Persson, P. O., Rydén, L., Darozhka, S. & Zaliauskiene, A. 2007. *Cleaner Production: Technologies and Tools for Resource Efficient Production,* Uppsala, Sweden, The Baltic University Press. ISBN: 9197552615

Nowacki, H. 2010. Five decades of Computer-Aided Ship Design. *Computer-Aided Design,* 42**,** 956-969. http://dx.doi.org/10.1016/j.cad.2009.07.006

OECD 2008. Measuring material flows and resource productivity: Volume 1 The OECD Guide. OECD.

Ohno, T. 1988. *Toyota production system: beyond large-scale production*, Florida, USA, Productivity press. ISBN: 9780915299140

Okay, O., Karacık, B., Güngördü, A., Ozmen, M., Yılmaz, A., Koyunbaba, N., Yakan, S., Korkmaz, V., Henkelmann, B. & Schramm, K.-W. 2014. Micro-organic pollutants and biological response of mussels in marinas and ship building/breaking yards in Turkey. *Science of The Total Environment,* 496**,** 165-178. https://doi.org/10.1016/j.scitotenv.2014.07.035

Ordoñez, I. & Rahe, U. 2013. Collaboration between design and waste management: Can it help close the material loop? *Resources, Conservation and Recycling,* 72**,** 108-117. http://dx.doi.org/10.1016/j.resconrec.2013.01.002

Ormond, T. 2012. Hong Kong Convention and EU Ship recycling Regulation: Can they change bad industrial practices soon. *Elni Review,* 2.

OSHA 2010. Safe Work Practices for Shipbreaking. Occupational Safety and Health Administration, U.S. Department of Labor.

Overgaard, S., Kristensen, D., Woods, M. & Stuer-Lauridsen, F. 2013. Feasibility Study for Environmentally sound Ship Dismantling. Denmark: Litehauz for UNEP.

Papanikolaou, A. 2014. *Ship Design: Methodologies of Preliminary Design*, Springer. ISBN: 9789401787505

Papanikolaou, A., Andersen, P., Kristensen, H. O. H., Levander, K., Riska, K., Singer, D. & Vassalos, D. 2009. State of the art report on design for X. *10th Int. Marine Design Conference (IMDC'09).*

Pavnaskar, S. J., Gershenson, J. K. & Jambekar, A. B. 2003. Classification scheme for lean manufacturing tools. *International Journal of Production Research,* 41**,** 3075-3090. https://doi.org/10.1080/0020754021000049817

Perry, N., Bernard, A., Laroche, F. & Pompidou, S. 2012. Improving design for recycling – Application to composites. *CIRP Annals - Manufacturing Technology,* 61**,** 151-154. http://dx.doi.org/10.1016/j.cirp.2012.03.081

Petek, J. & Glaviç, P. 2000. Improving the sustainability of regional cleaner production programs. *Resources, Conservation and Recycling,* 29**,** 19-31. http://dx.doi.org/10.1016/S0921-3449(99)00051-8

Porteous, A. 2005. Why energy from waste incineration is an essential component of environmentally responsible waste management. *Waste Management,* 25**,** 451-459. https://doi.org/10.1016/j.wasman.2005.02.008

Pourali, M. 2010. Application of Plasma Gasification Technology in Waste to Energy - Challenges and Opportunities. *IEEE Transactions on Sustainable Energy,* 1**,** 125-130. https://doi.org/10.1109/TSTE.2010.2061242

Psomopoulos, C. S., Bourka, A. & Themelis, N. J. 2009. Waste-to-energy: A review of the status and benefits in USA. *Waste Management,* 29**,** 1718-1724. https://doi.org/10.1016/j.wasman.2008.11.020

Rahman, S. M. & Mayer, A. L. 2015. How social ties influence metal resource flows in the Bangladesh ship recycling industry. *Resources, Conservation and Recycling,* 104**,** 254-264. https://doi.org/10.1016/j.resconrec.2015.07.022

Rao, M. P. 2006. A performance measurement system using a profit‐linked multi‐factor measurement model. *Industrial Management & Data Systems,* 106**,** 362-379. https://doi.org/10.1108/02635570610653506

Reddy, M. S., Basha, S., Joshi, H. V., Sravan Kumar, V. G., Jha, B. & Ghosh, P. K. 2005. Modeling the energy content of combustible ship-scrapping waste at Alang–Sosiya, India, using multiple regression analysis. *Waste Management,* 25**,** 747-754. http://dx.doi.org/10.1016/j.wasman.2004.11.009

Reddy, M. S., Basha, S., Kumar, V. S., Joshi, H. & Ghosh, P. 2003. Quantification and classification of ship scraping waste at Alang–Sosiya, India. *Marine pollution bulletin,* 46**,** 1609-1614. https://doi.org/10.1016/S0025-326X(03)00329-1

Ribeiro, J. S. & Gomes, J. d. O. 2015. Proposed Framework for End-of-life Aircraft Recycling. *Procedia CIRP,* 26**,** 311-316. http://dx.doi.org/10.1016/j.procir.2014.07.048

Robindesbois.org. 2006-16. *Shipbreaking – bulletin of information and analysis on end-of-life ships* [Online]. Robin des Bois. Available: http://www.robindesbois.org/en/a-la-casse-bulletin-dinformation-et-danalyses-sur-les-navires-en-fin-de-vie/ [Accessed].

Robindesbois.org. 2012. *Shipbreaking – bulletin of information and analysis on end-of-life ships* [Online]. Robin des Bois. Available: http://www.robindesbois.org/en/a-la-casse-bulletin-dinformation-et-danalyses-sur-les-navires-en-fin-de-vie/ [Accessed 06.03.2017].

Robindesbois.org. 2015. *Shipbreaking – bulletin of information and analysis on end-of-life ships* [Online]. Robin des Bois. Available: http://www.robindesbois.org/en/a-la-casse-bulletin-dinformation-et-danalyses-sur-les-navires-en-fin-de-vie/ [Accessed 06.03.2017].

Rodríguez, M. T., Andrade, L. C., Bugallo, P. B. & Long, J. C. 2011. Combining LCT tools for the optimization of an industrial process: material and energy flow analysis and best available techniques. *Journal of hazardous materials,* 192**,** 1705-1719. https://doi.org/10.1016/j.jhazmat.2011.07.003

Rogne, K. 1974. Redesigning the design process: Superstructures of ships. *Applied ergonomics,* 5**,** 213-218. https://doi.org/10.1016/0003-6870(74)90004-0

Rozenveld, W. 2010. Safe & Sustainable Ship Recycling. *Sustainable Shipping Conference 2010: From the Cradle to the Grave.* Miami.

Ruj, B. & Ghosh, S. 2014. Technological aspects for thermal plasma treatment of municipal solid waste—A review. *Fuel Processing Technology,* 126**,** 298-308. http://dx.doi.org/10.1016/j.fuproc.2014.05.011

Rybicka, J., Tiwari, A., Del Campo, P. A. & Howarth, J. 2015. Capturing composites manufacturing waste flows through process mapping. *Journal of Cleaner Production,* 91**,** 251-261. https://doi.org/10.1016/j.jclepro.2014.12.033

SAJ 2009. Shipbuilding Statistics March 2009. The Ship Builders' Association of Japan.

SAJ 2016. Shipbuilding Statistics March 2016. The Ship Builders' Association of Japan.

Sakai, S.-i., Yoshida, H., Hiratsuka, J., Vandecasteele, C., Kohlmeyer, R., Rotter, V., Passarini, F., Santini, A., Peeler, M., Li, J., Oh, G.-J., Chi, N., Bastian, L., Moore, S., Kajiwara, N., Takigami, H., Itai, T., Takahashi, S., Tanabe, S., Tomoda, K., Hirakawa, T., Hirai, Y., Asari, M. & Yano, J. 2014. An international comparative study of end-of-life vehicle (ELV) recycling systems. *Journal of Material Cycles and Waste Management*, 16**,** 1-20. http://dx.doi.org/10.1007/s10163-013-0173-2

Salem, O., Solomon, J., Genaidy, A. & Minkarah, I. 2006. Lean construction: From theory to implementation. *Journal of management in engineering*. http://dx.doi.org/10.1061/(ASCE)0742-597X(2006)22:4(168)

Sarraf, M. 2010. The ship breaking and recycling industry in Bangladesh and Pakistan. Washington, D.C.: World Bank.

SEP 2016. Ship recycling: reducing human and environmental impacts. *Science for Environment Policy Thematic Issue 55*. Bristol: Univ. of the West of England for European Commission DG Environment.

Severo, E. A., Guimarães, J. C. F. d. & Dorion, E. C. H. 2016. Cleaner production and environmental management as sustainable product innovation antecedents: A survey in Brazilian industries. *Journal of Cleaner Production*. http://dx.doi.org/10.1016/j.jclepro.2016.06.090

Shah, R. & Ward, P. T. 2003. Lean manufacturing: context, practice bundles, and performance. *Journal of operations management,* 21**,** 129-149. https://doi.org/10.1016/S0272-6963(02)00108-0

Sivaprasad, K. 2010. *Development of best practices for ship recycling process*. PhD, Department of Ship technology, Cochin University of Science and technology.

Sivaprasad, K., Jayaram, S. & Nandakumar, C. 2012. Recycling of Decommissioned Naval Fleet. *International Journal of Innovative Research and Development,* 1**,** 318-329. http://www.ijird.com/index.php/ijird/article/view/34959

Sivaprasad, K. & Nandakumar, C. G. 2013. Design for ship recycling. *Ships and Offshore Structures*, 8**,** 214-223. http://dx.doi.org/10.1080/17445302.2012.669264

Slack, N., Chambers, S. & Johnston, R. 2010. *Operations management,* Essex, England, Pearson Education. ISBN: 9780273731603

Söderholm, P. & Ejdemo, T. 2008. Steel scrap markets in Europe and the USA. *Minerals & Energy-Raw Materials Report,* 23**,** 57-73. http://dx.doi.org/10.1080/14041040802018497

Solesvik, M. Z. A collaborative design in shipbuilding: two case studies. 5th IEEE International Conference on Industrial Informatics 2007. IEEE, 299-304.

Soo, V. K., Compston, P. & Doolan, M. 2015. Interaction between New Car Design and Recycling Impact on Life Cycle Assessment. *Procedia CIRP,* 29**,** 426-431. http://dx.doi.org/10.1016/j.procir.2015.02.055

SpecTec. 2015. *SFI Codification System* [Online]. Available: http://www.spectec.net/en/maritime/sfi-codification-system [Accessed 19.01.2016].

Stanisavljevic, N. & Brunner, P. H. 2014. Combination of material flow analysis and substance flow analysis: A powerful approach for decision support in waste management. *Waste Management and Research,* 32**,** 733-744. http://dx.doi.org/10.1177/0734242X14543552

Steelrates.com. 2015. *Scrap steel rate: Alang* [Online]. Alang: Steelrate.com. Available: http://steelrates.com/ [Accessed 01/10/2015].

Sterling, J. 2011. Cradle to Cradle Passport– towards a new industry standard in ship building. *OECD Workshop on Green Growth in Ship Building* [Online].

StockCharts.com. 2016. *Baltic Dry Index* [Online]. Stockcharts.com. Available: http://stockcharts.com/h-sc/ui?s=$BDI [Accessed 01/09/2016].

Stopford, M. 2009. *Maritime Economics,* London, Routledge. ISBN: 9780415275576

Storch, R. L. & Lim, S. 1999. Improving flow to achieve lean manufacturing in shipbuilding. *Production Planning & Control,* 10**,** 127-137. http://dx.doi.org/10.1080/095372899233280

Strulik, H. 2004. Solving Rational Expectations Models Using Excel. *The Journal of Economic Education,* 35**,** 269-283. http://dx.doi.org/10.3200/JECE.35.3.269-283

Sujauddin, M., Koide, R., Komatsu, T., Hossain, M. M., Tokoro, C. & Murakami, S. 2015. Characterization of ship breaking industry in Bangladesh. *Journal of Material Cycles and Waste Management,* 17**,** 72-83. http://dx.doi.org/10.1007/s10163-013-0224-8

Sujauddin, M., Koide, R., Komatsu, T., Hossain, M. M., Tokoro, C. & Murakami, S. 2016. Ship Breaking and the Steel Industry in Bangladesh: A Material Flow Perspective. *Journal of Industrial Ecology*. http://dx.doi.org/10.1111/jiec.12423

Sujauddin, M., Koide, R., Mohammed Mosharraf, H. & Murakami, S. Material flow analysis on ship breaking and recycling industry in Bangladesh. The 10th International Conference on EcoBalance, Yokohama, Japan, 2012.

Taj, S. 2008. Lean manufacturing performance in China: assessment of 65 manufacturing plants. *Journal of Manufacturing Technology Management,* 19**,** 217-234. http://dx.doi.org/10.1108/17410380810847927

Tang, J. & Brunner, P. H. 2013. Globalising MFA – Decision Support for Waste Management in Cities based on the Software STAN. *ISWA Guidelines & Reports.* International Solid Waste Association.

Tang, L., Huang, H., Hao, H. & Zhao, K. 2013. Development of plasma pyrolysis/gasification systems for energy efficient and environmentally sound waste disposal. *Journal of Electrostatics,* 71**,** 839-847. http://dx.doi.org/10.1016/j.elstat.2013.06.007

Thomas, H. R., Horman, M. J., Minchin Jr, R. E. & Chen, D. 2003. Improving labor flow reliability for better productivity as lean construction principle. *Journal of construction engineering and management,* 129**,** 251-261. http://dx.doi.org/10.1061/(ASCE)0733-9364(2003)129:3(251)

Tian, J. & Chen, M. 2014. Sustainable design for automotive products: Dismantling and recycling of end-of-life vehicles. *Waste Management,* 34**,** 458-467. http://dx.doi.org/10.1016/j.wasman.2013.11.005

Tseng, M.-L., Chiu, A. S. F., Lin, Y.-H. & Chinag, J.-H. 2006. The relationship of continuous improvement and cleaner production on operational performance: An empirical study in electronic manufacturing firms, Taiwan China. *International Journal of Management Science and Engineering Management,* 1**,** 71-80. http://dx.doi.org/10.1080/17509653.2006.10670999

UNESCO 2004. Impacts and challenges of a large coastal industry. Alang Sosiya Ship Breaking Yard, Gujarat, India. *Coastal region and small island papers 17.* Paris: UNESCO.

UNIDO-UNEP 2010. Taking stock and moving forward: The UNIDO–UNEP National Cleaner Production Centres. Vienna: UNEP; UNIDO; State Secretariat for Economic Affairs, Government of Switzerland.

Unnikrishnan, S. & Hegde, D. S. 2007. Environmental training and cleaner production in Indian industry—A micro-level study. *Resources, Conservation and Recycling,* 50**,** 427-441. http://dx.doi.org/10.1016/j.resconrec.2006.07.003

Upadhyay, G. B. 2002. *The problems and prospects of ship breaking industry in India with reference to Alang ship breaking yard.* PhD, Bhavnagar University.

USEPA 2000. *A Guide for ship scrappers : tips for regulatory compliance,* Washington D.C., DIANE Publishing. ISBN: 9781288862559

Van Berkel, R. Cleaner production for process industries: overview of the cleaner production concept and relation with other environmental management strategies. Chemeca 2000: Opportunities and Challenges for the Resource and Processing Industries, 2000a. Barton: Institution of Engineers, Australia, 12.

Van Berkel, R. 2000b. Cleaner Production in Australia: revolutionary strategy or incremental tool? *Australian Journal of Environmental Management,* 7**,** 132-146. http://dx.doi.org/10.1080/14486563.2000.10648495

van Bruinessen, T., Hopman, H. & Smulders, F. 2013. Towards a Different View on Ship Design: The Development of Ships Observed Through a Social-Technological Perspective. *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering.* American Society of Mechanical Engineers.

van Heerden, D.-J. & Curran, R. 2010. Aircraft Disposal and Recycling. *In:* Blockley, R. & Shyy, W. (eds.) *Encyclopedia of Aerospace Engineering.* John Wiley & Sons, Ltd. ISBN: 9780470754405 https://doi.org/10.1002/9780470686652.eae355

van Schaik, A. & Reuter, M. A. 2004. The optimization of end-of-life vehicle recycling in the european union. *JOM,* 56**,** 39-43. http://dx.doi.org/10.1007/s11837-004-0180-9

Vardar, E. 2009. Fate of Ship breaking waste in Turkey. Brussels: NGO Platform on Ship breaking.

Vardar, E., Kumar, R., Dao, R., Harjono, M., Besieux, M., Brachet, I. & Wrzoncki, E. 2005. End of Life Ships The Human Cost of Ship Breaking: A greenpeace-FIDH report in cooperation with YPSA.

Vassalos, D. 2009. Risk-based ship design. *In:* Papanikolaou, A. D. (ed.) *Risk-based ship design: Methods, Tools and Applications.* Berlin: Springer-Verlag. ISBN: 9783540890416

Veeke, H. P., Ottjes, J. A. & Lodewijks, G. 2008. *The Delft systems approach: Analysis and design of industrial systems,* London, Springer Science & Business Media. ISBN: 9781849967457

Veenstra, A. W. & Ludema, M. W. 2006. The relationship between design and economic performance of ships. *Maritime Policy & Management,* 33**,** 159-171. http://dx.doi.org/10.1080/03088830600612880

Vermeulen, I., Van Caneghem, J., Block, C., Baeyens, J. & Vandecasteele, C. 2011. Automotive shredder residue (ASR): Reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals' valorisation. *Journal of Hazardous Materials,* 190**,** 8-27. http://dx.doi.org/10.1016/j.jhazmat.2011.02.088

Waring, J. J. & Bishop, S. 2010. Lean healthcare: rhetoric, ritual and resistance. *Social science & medicine,* 71**,** 1332-1340. https://doi.org/10.1016/j.socscimed.2010.06.028

Womack, J. P. & Jones, D. T. 2010. *Lean thinking: banish waste and create wealth in your corporation,* New York, USA, Free Press. ISBN: 9780743231640

Womack, J. P., Jones, D. T. & Roos, D. 1990. *Machine that changed the world,* New York, USA, Scribner. ISBN: 9780892563500

Xu, H. L., Wang, H., Xu, H., Kou, X., Li, C., Yan, H. S., Du, Z. F. & Xu, W. H. 2012. Discuss on Green Shipbuilding Technology: Design and Material. *Advanced Materials Research,* 490**,** 3296-3300. https://doi.org/10.4028/www.scientific.net/AMR.490-495.3296

Yang, M. G. M., Hong, P. & Modi, S. B. 2011. Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing firms. *International Journal of Production Economics,* 129**,** 251-261. https://doi.org/10.1016/j.ijpe.2010.10.017

Zeng, S. X., Meng, X. H., Yin, H. T., Tam, C. M. & Sun, L. 2010. Impact of cleaner production on business performance. *Journal of Cleaner Production,* 18**,** 975-983. http://dx.doi.org/10.1016/j.jclepro.2010.02.019

Curriculum vitae

Kanu Priya Jain was born on 13th Feb, 1985 in Ghaziabad, Uttar Pradesh, India. He studied in Birla Institute of Technology and Science, Pilani, Rajasthan, India from 2002 to 2006 to obtain a degree of Bachelor of Science in Marine Engineering. He then obtained the professional qualifications of Marine Engineering Officer (Class IV) from the Directorate General of Shipping, Government of India after successfully passing the examinations conducted in accordance with STCW 1978, the international standards developed by International Maritime Organization. This professional certification allowed him to serve on board sea-going, international merchant ships. He worked for Bernhard Schulte Ship Management as Marine Engineer on various ships including car carriers and container ships from 2007 to 2011. He obtained an M.Sc. in Marine Transport Management (with distinction) from Newcastle University, England in 2012. He analysed the impacts of Energy Efficiency Design Index (EEDI) regulations on ship owners for his M.Sc. thesis titled *Impacts of Energy Efficiency Design Index*.

In May 2013, Kanu started working as a Ph.D. candidate at the Department of Maritime and Transport Technology of Delft University of Technology, The Netherlands. His research on ship recycling, presented in this dissertation is part of a collaborative project with Tianjin University, China. The project is co-ordinated by International Ship Recycling Organization, ISRA and is supported by industrial organizations such as Sea2cradle B.V., Lloyd's Register, North Sea Foundation and DAMEN Shipyards Group.

In addition to the research presented in this dissertation, Kanu also assisted in educational tasks at TU Delft. These included a couple of lectures to M.Sc. students for the course *MTM1414: Maritime Finance, Business and Law*, a lunch lecture on ship recycling to M.Sc. students, supervising a Master's student during his internship on a Chinese recycling yard and another Master's student for his exchange program, and supervising four Bachelor students for their Bachelor-end project titled *Design for recycling: technical implementations to improve the process of ship recycling*.

Publications

Jain, K.P. & Pruyn J. 2017. An overview of the global ship recycling industry. *Reference Module in Materials Science and Materials Engineering*, Accepted, Elsevier Inc., ISBN: 978-0-12-803581-8

Jain, K. P. & Pruyn, J. 2016. Economic Impact Assessment of Using a Plasma Gasification Plant on a Large Ship Recycling Yard. *In:* Clarke, W. P., Cossu, R., Diaz, L. F., Liu, J., Matsuto, T., Nelles, M. & Stegmann, R., eds. Venice 2016 - Sixth International Symposium on Energy from Biomass and Waste, 2016 Venice. Padova, Italy: CISA Publisher, ISBN: 978-88-6265-009-0.

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2017. Material Flow Analysis (MFA) as a tool to improve ship recycling. *Ocean Engineering,* 130, 674-683, http://dx.doi.org/10.1016/j.oceaneng.2016.11.036

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2016b. Quantitative assessment of material composition of end-of-life ships using onboard documentation. *Resources, Conservation and Recycling,* 107, 1-9, http://dx.doi.org/10.1016/j.resconrec.2015.11.017

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2016. Improving ship design process to enhance ship recycling. *In:* Soares, C. G. & Santos, T. A., eds. 3rd International Conference on Maritime Technology and Engineering (MARTECH 2016), 2016a Lisbon, Portugal. London, U.K.: CRC Press - Taylor and Francis Group, 663-671, https://doi.org/10.1201/b21890-86

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2014. Influence of ship design on ship recycling. *In:* Soares, C. G. & Santos, T. A., eds. 2nd International Conference on Maritime Technology and Engineering (MARTECH 2014), 2014 Lisbon, Portugal. London, U.K.: CRC Press - Taylor and Francis Group, 269-276, https://doi.org/10.1201/b17494-37

Jain, K. P., Pruyn, J. F. J. & Hopman, J. J. 2013. Critical Analysis of the Hong Kong International Convention on Ship Recycling. *In:* Vaninsky, A., Semonov, E. & Bolitin, A., eds. World Academy of Science, Engineering and Technology Conference, 2013 Dubai. Dubai: WASET, 684-692, eISSN: 2010-3778

Synopsis

Ship recycling marks the end of life of a ship. A large number of ships are recycled on substandard recycling yards due to high price offered to ship owners. On the contrary, green ship recycling yards struggle to increase their market share due to high operational costs. Such market dynamics undermines the contribution of the ship recycling industry towards sustainability. Therefore, to improve the competitiveness of green yards, this dissertation investigates the use of the concept of cleaner production to ship recycling. As a result, two types of measures are suggested. First, the ship based measures, which includes quantification of materials of end-of-life ships and design-for-recycling. Second, the yard based measures, which includes material flow analysis on a yard and plasma gasification of waste. These measures are likely to increase revenues, reduce costs and improve planning of green recycling yards.

ISBN: 978-94-6299-657-1