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**DOI**

[10.1016/j.oceaneng.2016.11.036](https://doi.org/10.1016/j.oceaneng.2016.11.036)

**Publication date**

2017

**Document Version**

Accepted author manuscript

**Published in**

Ocean Engineering

**Citation (APA)**

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>

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# Material flow analysis (MFA) as a tool to improve ship recycling

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## Abstract

The ship owner's decision to select a recycling yard for dismantling and recycling an end-of-life ship is primarily influenced by the price offered for purchasing the ship. The recycling yards offering 'green' recycling services generally quote lower prices than other yards due to the higher cost of dismantling a ship by following international ship recycling regulations and health, safety and environmental (HSE) management systems. Such 'green' recycling yards must either lower their costs or increase their revenues to offer better prices to ship owners compared to the yards which have primitive or non-existent HSE standards. This article analyzes multi-disciplinary scientific tools and techniques that can be used to make 'green' ship recycling economically attractive to ship owners without compromising HSE standards. Material flow analysis (MFA) has been found to be a suitable tool to analyze and plan the ship recycling process. This allows ship recycling yards to better manage waste and resources, thereby reducing costs. The material flow diagrams for a bulk carrier (case ship), showing the generic ship recycling process, are also developed and discussed. The analysis approach used in this article shows one way of introducing analytical tools into ship recycling planning and process assessment.

## Keywords

Ship recycling, ship breaking, green ship recycling, material flow analysis, waste management.

## 1 Introduction

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.

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 paper. According to an estimate by Abdullah et al. (2012), 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.

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

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

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

## 78 **2 Methods and data**

79 The authors of this article gathered inspiration from both operations management and environmental  
80 engineering to implement a well-known technique to improve the ship recycling industry. Therefore,  
81 this article reviews analytical tools of both domains. The challenges faced by 'green' ship recycling  
82 industry and the inability of various operations management tools to address those challenges are  
83 discussed. This article concludes that MFA, an analytical tool used in environmental engineering, is  
84 the most practical tool of those reviewed. The methodology and input data for carrying out MFA on a  
85 ship recycling yard is explained. The MFA is implemented using a 2006 built, 11044 tonnes  
86 lightweight bulk carrier as a case study for assessing its applicability to the ship recycling industry.  
87 The application of MFA for various ship recycling planning related tasks such as investigating the  
88 flows of economic and non-economic value streams on a yard, assessing and planning the ship  
89 recycling process, and anticipating various recycling scenarios are also discussed. The article  
90 concludes by explaining the importance and shortcomings of applying MFA to the ship recycling  
91 industry. It also summarizes the key takeaways of this research.

### 92 **2.1 Operations management**

93 Operations management is the systematic planning, execution and control of operations (Slack et al.,  
94 2010). 'Operations' is an umbrella term that includes services and manufacturing. Operations  
95 management involves scheduling work, assigning resources, managing inventories, assuring quality  
96 standards and process-type decisions such as capacity decisions, maintenance policies, equipment

97 selection, worker-training options and the sequence for making individual items in a product-mix set  
98 (Gupta and Starr, 2014).

99 In the last few decades, due to significantly increased levels of competitiveness in modern industry, a  
100 range of methodologies and techniques aimed at improving the performance, productivity and  
101 profitability of the operational activity have been developed (Grünberg, 2003, Hernandez-Matias et al.,  
102 2008, Hernandez-Matias et al., 2006, Shah and Ward, 2003). These techniques can be broadly  
103 classified into two main categories: diagnostic tools (process mapping, process flowcharting, value  
104 stream mapping, pareto analysis, fishbone diagrams, etc.) and improvement tools (just-in-time(JIT),  
105 total quality management (TQM), total preventive maintenance (TPM), theory of constraints (TOC),  
106 business process reengineering (BPR), etc.). A wide variety of such management practices, methods,  
107 tools and techniques are encompassed under a production approach called lean manufacturing  
108 (Womack and Jones, 2010, Womack et al., 1990), based on the Toyota Production System (Ohno,  
109 1988).

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

117 Lean thinking has been successfully applied to the industries where inputs are transformed into outputs.  
118 This includes the manufacturing (Detty and Yingling, 2000, Shah and Ward, 2003, Taj, 2008, Yang et  
119 al., 2011), healthcare (Brandao de Souza, 2009, Jones and Mitchell, 2006, Mazzocato et al., 2010,  
120 Waring and Bishop, 2010), construction (Ballard and Howell, 1994, Koranda et al., 2012, Salem et al.,  
121 2006, Thomas et al., 2003) and process industry (Abdulmalek and Rajgopal, 2007, King, 2009, Melton,  
122 2005). However, it must still be investigated whether lean and other aforementioned tools can be  
123 implemented to improve the competitiveness of 'green' ship recycling.

### 124 **2.1.1 Lean manufacturing tools**

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

### 135 **2.1.2 Diagnostic tools**

136 The diagnostic tools such as process mapping can be helpful in understanding the generic ship  
137 recycling process and identifying the problem areas that can be targeted not only to develop and make  
138 'green' ship recycling competitive but also to improve the ship recycling industry on the whole. In any  
139 industrial process there are three types of flows i.e. information, product and resources (Veeke et al.,  
140 2008). The information flow contains the technical data controlling the operation itself. The product  
141 flow is initiated due to the transformation of raw materials into delivered products as a result of the  
142 industrial process. The flow of resources includes the people and means required to make the product.  
143 Resources must enter the system and leave the system as 'used' resources. From a ship recycling  
144 yard's point of view, the product flow (i.e. the flow of materials) is the most critical flow because it  
145 influences the revenue generation and the cost factors of a ship recycling project. These cost factors  
146 include the amount of resources (labor, cranes, forklifts etc.) required to dismantle a ship, the amount

147 of waste and its management strategy. Therefore, a process mapping tool that focuses on material flow  
148 is ideal for analyzing and improving the ship recycling process.

### 149 **2.1.3 Improvement tools**

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

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

## 164 **2.2 Environmental engineering**

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

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

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

194 An MFA can be carried out using the software STAN (Cencic and Rechberger, 2008) not only to  
195 produce a graphical representation of a waste management system but also to determine the types of



196 materials that flow into, within and out of the system. This can help manage the waste in such a way  
 197 that the recycling process is not threatening to human health and environment, assists resource  
 198 conservation and allows segregation of non-recyclables from recyclables so that an appropriate  
 199 disposal strategy (landfill or energy recovery) can be implemented.

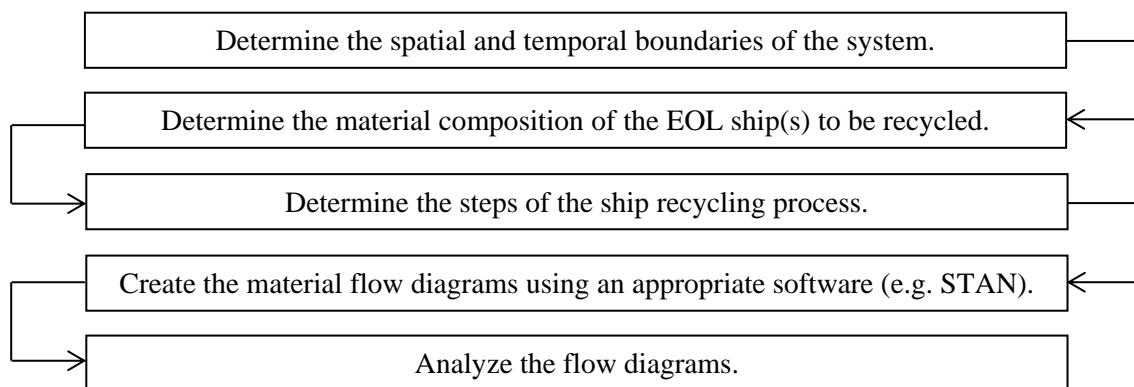
200 In this article; waste, from a ship recycling yard's perspective is defined as any substance, material or  
 201 object originating from dismantling an EOL ship and is required to be discarded and disposed  
 202 appropriately in accordance with applicable laws, regulations, management standards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

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

218 There are clear advantages of using MFA as an analysis tool on a ship recycling yard but the quality of  
 219 results depend on the quality of the input data. Data collection has historically been a problem in the  
 220 ship recycling industry because of skepticism among recycling yards and a lack of co-ordination  
 221 among the various stakeholders. Moreover, since research in this area of study is still in its preliminary  
 222 stage, few databases collecting the requisite data exist. Various authors (Demaria, 2010, Sarraf, 2010,  
 223 Sujauddin et al., 2014) have discussed this issue of unavailability of data hampering the research in  
 224 ship recycling field. In the next section of this article, authors discuss a methodology to collect data  
 225 and carry out MFA on a ship recycling yard.

### 226 **2.3 Methodology and input data for MFA on a ship recycling yard**

227 For carrying out an MFA on a ship recycling yard, the steps shown in Figure 1 can be followed. First,  
 228 the space and time boundaries of the system must be defined. Secondly, material composition of EOL  
 229 ship(s) to be recycled must be determined. Thirdly, various steps of the ship recycling process must be  
 230 established. Finally, flow diagrams can be created using the open source software 'STAN'. The flow  
 231 diagrams can be analyzed to meet the requisite objective.



232 **Figure 1: Step by step methodology for MFA on a ship recycling yard.**

### 233 2.3.1 Spatial and temporal boundary

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

### 242 2.3.2 Quantification of material composition of a ship

243 The study carried out by Jain et al. (2016b) determined that out of the nine studies (Adak, 2013,  
 244 Andersen et al., 2001, Andersen et al., 1999, Demaria, 2010, Hess et al., 2001, Hiremath et al., 2015,  
 245 Reddy et al., 2003, Sarraf, 2010, Sujauddin et al., 2014) available on the quantification of material  
 246 composition of EOL ships, none present a methodology that can be used by the ship recycling yards to  
 247 determine the material composition of an individual ship. Therefore, they presented a methodology  
 248 which determines the material composition of a 2006 built, 11044 tonnes lightweight handymax bulk  
 249 carrier on the basis of its lightweight distribution provided in its stability manual. For this research,  
 250 this particular ship is used as a case ship. The material composition of the case ship calculated by Jain  
 251 et al. (2016b) does not contain the values for the material stream 'liquids, chemicals and gases' (LCG)  
 252 because they considered that the most of the LCG material stream is operationally generated and is not  
 253 part of the ship's lightweight. The material composition of the case ship corrected for LCG material  
 254 stream is compiled in Table 1. The value for LCG material stream is taken from a study carried out by  
 255 Andersen et al. (2001) for a bulk carrier.

256 **Table 1: Material composition of an 11044 T lightweight handymax bulk carrier based on Andersen et al. (2001), Jain**  
 257 **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

### 258 2.3.3 Steps of the ship recycling process

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

### 272 2.3.4 Material flow diagrams

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

### 282 2.3.5 Assumptions

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

295 **Table 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.

296 The assumptions made here represent a scenario where there is an existing scrap market for ferrous  
 297 and non-ferrous scrap, and a second-hand market for items such as electrical and electronic waste,  
 298 joinery, liquids (waste oil, sludge, fuel oil, lube oil, etc.) and machinery. For example, in Apr-2016  
 299 electrical cables (Rs. 100-150 per kg), electric motors (Rs. 70-80 per kg), glass wool insulation sheets  
 300 (Rs. 2-4 per kg), sludge (Rs. 1-2 per kg), waste oil (Rs. 600-1100 per barrel), scrap machinery (Rs. 65-  
 301 80 per kg), etc. were being legally sold in the second hand market at Alang, India at the prices  
 302 mentioned in the brackets (Agarwal, 2016).



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 2.

### 3 Results

#### 3.1 Material flow diagrams

The spatial boundary for the MFA of the case ship is the ship recycling yard while the temporal boundary is the amount of time required to recycle this ship. The most basic level of the flow diagram for recycling of the case ship (based on the assumptions mentioned in Table 2), developed by software STAN, is shown by Figure 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 3, Figure 4 and Figure 5 respectively. These diagrams provide more insight into the basic level of the ship recycling process (Figure 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 box outlined in blue represents 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.

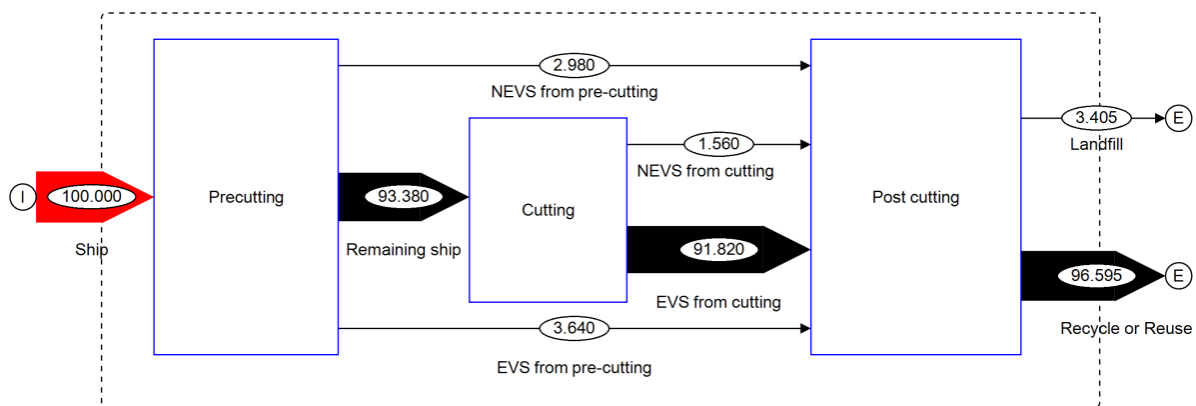
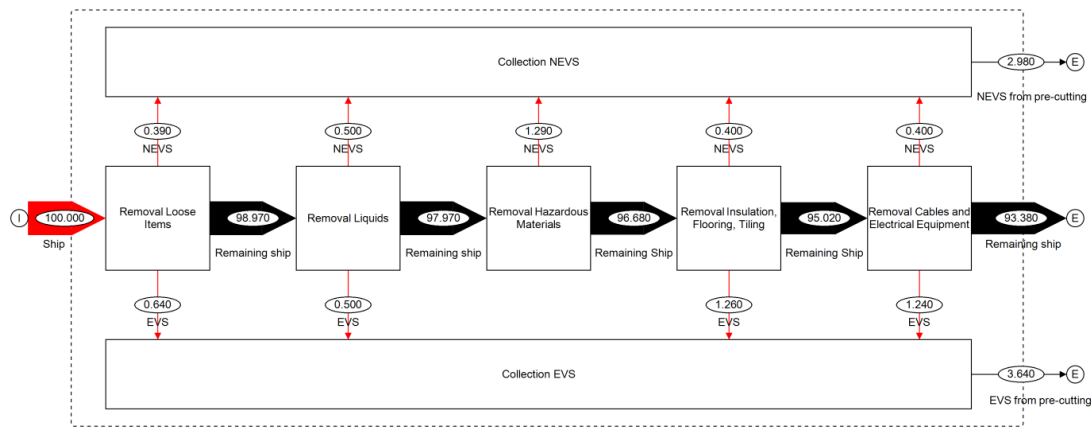


Figure 2: Ship recycling process of the case ship showing the quantities of material flow in terms of percentage of LDT.

##### 3.1.1 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

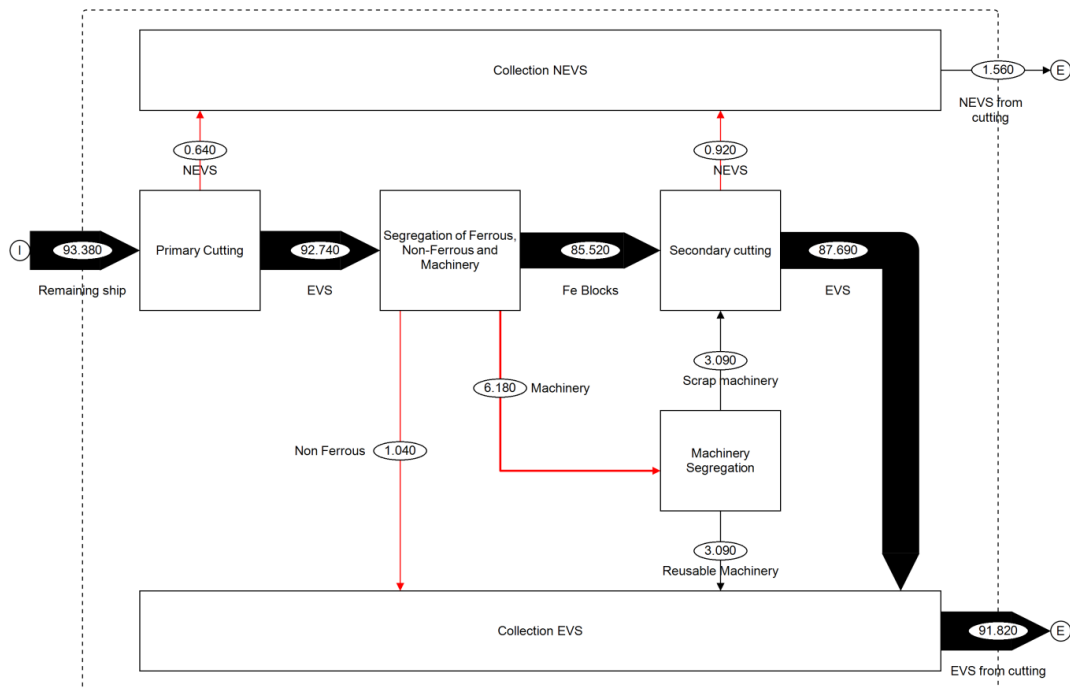
341 safely. Based on these assumptions, the assumptions made in Table 2 and the values of material  
 342 streams (Table 1), it is estimated by MFA that 2.98% and 3.64% of LDT of the case ship would  
 343 originate as NEVS and EVS respectively from the pre-cutting process. The remaining ship (93.38% of  
 344 LDT) would flow into the next process, cutting.



345  
 346 **Figure 3: Pre-cutting process of the case ship showing the quantities of material flow in terms of percentage of LDT.**

347 **3.1.2 Cutting**

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



354  
 355 **Figure 4: Cutting process of the case ship showing the quantities of material flow in terms of percentage of LDT.**

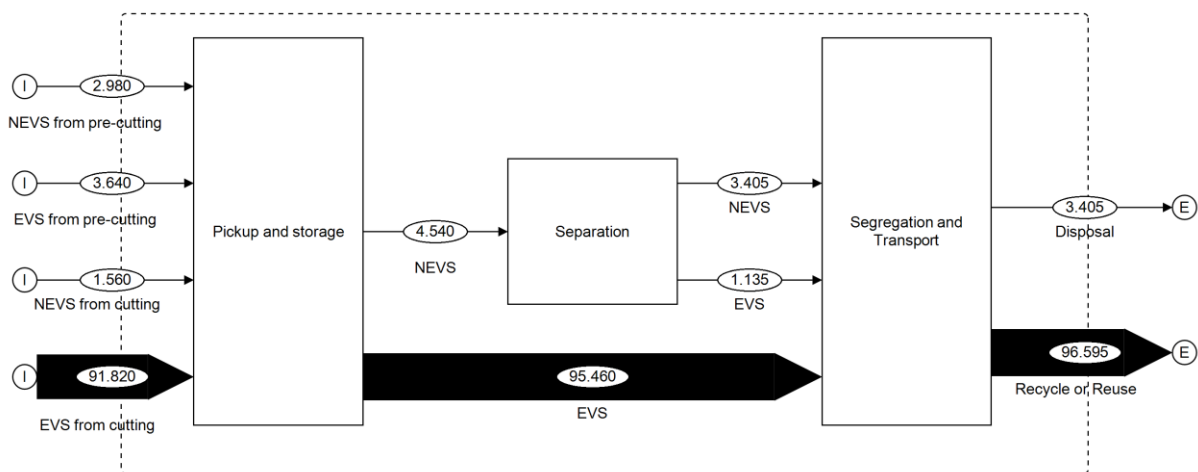
356 Both 'primary cutting' and 'secondary cutting' sub-processes are connected by a 'segregation of  
 357 ferrous, non-ferrous and machinery' sub-process, which depicts the segregation of ferrous blocks, non-  
 358 ferrous items and machinery. It also depict the transfer of bigger blocks from the primary cutting area

359 to the secondary cutting area. The ferrous blocks and obsolete machinery having no second-hand value  
 360 (scrap machinery) acts as an input to the 'secondary cutting'. Non-ferrous items, owing to their small  
 361 size, do not need to be fed into the sub-process 'secondary cutting'. The 'secondary cutting' is the  
 362 process where ferrous blocks are cut into steel plates and smaller pieces of steel scrap while the scrap  
 363 machinery is cut into the smaller pieces of machinery scrap.

364 The processes of 'primary cutting' and 'secondary cutting' are executed mainly using gas cutting  
 365 torches. The cutting process results mainly in an economic value stream owing to the high value of  
 366 ferrous and non-ferrous scrap. The only non-economic value stream out of the cutting process is paint  
 367 chips and other waste which can neither be sold in the second hand market nor can be recycled as  
 368 scrap. Based on the values of material streams (Table 1) and the assumptions made in the beginning of  
 369 this section (Table 2), it is estimated by the MFA that 1.56% and 91.82% of LDT of the case ship  
 370 would originate as NEVS and EVS respectively from the cutting process. Both these streams, along  
 371 with NEVS and EVS from the pre-cutting process, are fed into the post-cutting process.

### 372 3.1.3 Post-cutting

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



389 **Figure 5: Post-cutting process of the case ship showing the quantities of material flow in terms of percentage of LDT.**

390 Based on the assumptions made in the beginning of this section (Table 2) and the values of material  
 391 streams (Table 1), it is estimated by means of an MFA that 3.40% of LDT of the case ship would be  
 392 sent for disposal (in most cases to a landfill site) and 96.60% of LDT of the case ship can either be  
 393 reused or recycled. This effectively means that recycling an 11044 LDT handybulk carrier would  
 394 result in 375 T (3.40%) of waste needing either landfill or other disposal techniques while the

395 remaining amount 10669 T (96.60%) can either be recycled or reused by selling in the scrap market, if  
 396 the assumptions made in this research are found true. These figures also assume that about 25% of the  
 397 weight of the NEVS can be extracted as EVS during the 'separation' sub-process of the post-cutting  
 398 process. This value can change depending on the separation capacity and techniques employed by the  
 399 recycling yard.

400 The amount of EVS and NEVS obtained from each sub-process of recycling the case ship as derived  
 401 from the MFA diagrams for the applied assumptions is shown in Table 3.

402 **Table 3: The quantities of economic and non-economic value streams obtained from each sub-process of recycling the**  
 403 **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

## 404 **4 Discussion**

### 405 **4.1 Data accuracy**

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

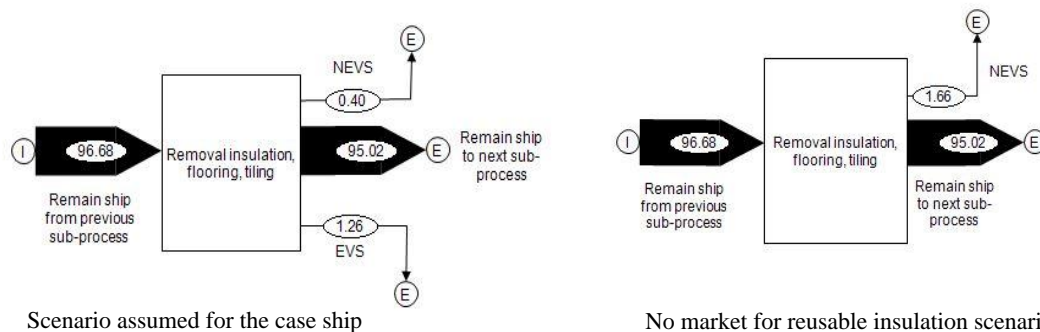
412 The MFA shown in this article is only for one ship under certain assumptions. However, ship  
 413 recycling yards recycle several ships at the same time in most cases. Therefore, an MFA might be  
 414 carried out for all the ships together. In that case, the spatial boundary still remains the same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

## 420 4.2 MFA scenarios

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

### 438 4.2.1 Case 1: decision making on reusable insulation

439 In certain cases, all the insulation originating from the EOL ship must be disposed, becoming a part of  
 440 NEVS. For example, in certain ship recycling countries no market for reusable insulation exists; while  
 441 on certain ships, insulation is glued to the ship structure and thus it is damaged in the removal process  
 442 to such an extent that it cannot be sold in the second-hand market. In such scenarios, MFA diagrams of  
 443 the ship recycling process would change drastically, altering the recycling costs and revenue  
 444 generating capability of the sub-process 'removal of insulation, flooring and tiling' as shown in Figure  
 445 6.



446

Scenario assumed for the case ship

No market for reusable insulation scenario

447 **Figure 6: Material flowing in and out of the sub-process 'removal insulation, flooring and tiling' in two different**  
 448 **scenarios.**

449 If scraping the insulation of a certain section of the steel hull is time consuming, the ship recycling  
 450 yard might even consider throwing away the entire section of steel hull along with the insulation glued  
 451 to it. In such case, certain portion of 95.02% of the remaining ship flowing to the next sub-process  
 452 would also end up in the NEVS. The weight of such a hull portion (steel and insulation) flowing into  
 453 NEVS depends on the area and thickness of the steel and insulation. Considering the relative thickness  
 454 of the steel and the insulation on a typical bulk carrier, it can be concluded that a recycling yard would  
 455 end up discarding 8 times the weight in steel, for each ton/percent of insulation. This results in 13.28%  
 456 of LDT flowing into NEVS along with 1.66% of LDT for insulation. Such a scenario would result in a  
 457 much bigger impact on the recycling yards' revenue generation than the scenario for the case ship  
 458 (shown in Figure 6). The scenario shows a four times increase in NEVS, from 0.4% LDT to 1.66%  
 459 LDT; while the throw-away-all scenario would lead to 37 times increase in the NEVS from 0.4% LDT  
 460 to 14.94% LDT. For the case ship, the drop in revenue against today's material prices (USD 275 per  
 461 ton of steel (Steelrates.com, 2015)) will be USD 400,000, allowing the yard to compare this figure



462 with the costs of removal of the insulation glued to the steel. The drop in revenue due to no resale of  
463 insulation (USD 14,000 at an average rate of USD 100 per ton of glass wool insulation in the second  
464 hand market in India (Agarwal, 2015)) results from an unfavourable decision during the building  
465 phase of the vessel.

#### 466 **4.2.2 Case 2: calculating material handling capacity**

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

#### 479 **4.3 Importance of applying MFA in ship recycling**

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

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

### 493 **5 Conclusions**

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

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

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

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

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

## 530 **Acknowledgements**

531 The authors of this article would like to acknowledge the support of Gieskes Strijbis Fonds for funding  
532 this research project on Green Ship Recycling which is performed by the consortium led by Delft  
533 University of Technology, The Netherlands and Tianjin University, China along with industrial  
534 partners Sea2Cradle B.V., International Ship Recycling Association (ISRA) and Lloyds Register.

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