Circular Ship Design

Defining a Framework for Implementing the Circular Economy Principles into Ship Design

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Defining a Framework for Implementing the Circular Economy Principles into Ship Design

by

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Preface

This thesis report is the final result of my Master in Marine Technology at Delft University of Technology. The research focuses on the implementation of the circular economy principles in the ship design approach. When thinking about sustainability in shipping, many people directly associate this with alternative fuels but if the shipping industry wishes to reduce its environmental impact to zero, the whole supply chain needs to be considered. The concept of circularity has emerged as a beacon of sustainability, presenting both a challenge and an opportunity. I was not familiar with the circular economy principles before the start of this thesis, but this subject has challenged and inspired me through the past 9 months and I have become very enthusiastic about using the principles, also in my personal life. It has motivated me to encourage more and more people to be conscious about the use of (raw) materials and reconsider choices that are sometimes based on the argument 'that's how we have always done it'. I hope that as a result of this thesis, the discussion can be started on including the circular economy principles in the maritime sector. I honestly believe that if everybody would try to use the circular economy principles to their best ability, we can slow down climate change significantly.

This research has been conducted as an internship at Damen Shipyards at both the departments of Technology Management and Sustainability. First and foremost, I would like to express my deepest gratitude to my supervisors at Damen, Dewi Wesselman and Jeffrey Jacobs, whose expertise and unwavering support were instrumental in shaping this thesis. Their mentorship not only ignited my passion for this subject but also provided invaluable insights that guided the course of my research. Next to them, also many other Damen colleagues contributed to this thesis, helping me understand various aspects of the Damen way of working and the ship design process in general.

Secondly, I would like to thank my supervisor from Delft University of Technology; Jeroen Pruyn for his continuous and unconditional guidance and support throughout the project. For the extremely fast replies to my emails full of questions and the willingness to always help out.

Finally, I want to thank my family and friends for all the years of support during my studies and for providing me with the needed distraction during all the years of studying, especially during this research. A special thanks go out to Marijn van der Plas and my parents, Hans and Monique, who have read this whole report and provided me with good feedback.

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Summary

Sustainability for shipping is not only about changing the fuel we use but also about taking care of the materials we use for our vessels. The circular economy principles can be applied to change the current 'take-make-dispose' economy and increase sustainable waste reduction. In a circular economy, the aim is to let products maintain their added value for as long as possible and minimise waste. However, at this moment, ships are designed with a focus on functionality, cost and operability.

When looking at circularity in shipbuilding, not a lot of research has been done on the topic. On the other hand, more and more rules regarding circularity are being developed such as the HKC by the IMO, the EU SRR by the EU, and ISO standards regarding circularity. Ship reuse, repair and recycling are already common practices, but this often happens with an eye on cost instead of circularity. Unfortunately, circularity is not yet included in the design phase, stressing the need for research into this topic. There are no approaches for ship designers to take circularity into account during the design process, whilst this is quite common for consumer goods. To include circularity in the ship design process, a choice must first be made between the plethora of frameworks presented in literature.

In this research, the 10R framework is combined with the Material Circularity Indicator method as it offers practical insight and manageable effort to address circularity in ship design. The different R levels are Refuse, Reduce, Redesign, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover. For every R, design strategies can be identified that are already used in the design of consumer goods.

Looking at ship design, systems engineering has been chosen as the design approach that will be combined with the circular economy principles since this is the 'newer' and structured method, solving some flaws of other methods such as the design spiral associated with point-based design. Currently, Damen Shipyards does not have one clear design method, but the aim is to implement ship design as the overall design method. To include circularity in ship design, the difference between normal, consumer good design and ship design needs to be clear. It stands out that consumer goods are strongly influenced by fashion and advertising, whilst ship design is more about function and efficiency. Also, the design method for consumer goods is vaguer, whilst for ship design methods such as systems engineering clear guidelines are present. Also, with consumer products, the end user is further away from the designer, having a smaller influence.

Assessing the current focus level of circularity in design could be done by identifying key indicators such as use frequency, lifespan, cost, modularity, material choice and reliability. For example, when products are too expensive to repair, they will most likely be disposed of, and depending on the cost of refurbishing, remanufacturing and repurposing, they might be recycled.

The systems engineering approach is combined with circular design strategies and results in a framework of six steps. In this framework, it is possible to determine the circularity of a design and identify key directions for improvement. This way the framework proves the need for a (re)new(ed) system and systems can be redesigned with a focus on both functionality and circularity.

The framework is demonstrated through a case study on the wheelhouse. In the wheelhouse, several sub-systems are assessed on their current circularity level and one sub-system is chosen and redesigned by use of the framework. This sub-system, being the floor, is improved in circularity from 15% to 90%. Key to a working framework as proposed is the contact with suppliers, both to provide information and to increase the circularity of the products offered by them.

This research provides the first steps in the right direction of including the circular economy principles in ship design approaches. The end product of this research, the framework, can guide ship designers already in the early stages of the design process to create functional and circular designs.

Contents

Preface ii

Summary iv

List of Figures x

List of Tables xi

List of Abbreviations xii

List of Symbols xiii

1 Introduction 1
1.1 Problem definition 1
1.2 Research questions 2
1.3 Scope 2
1.4 Structure 3
1.5 Literature research 3

2 Current applications of circularity in shipbuilding 5
2.1 Previous research 5
2.2 Regulations 7
2.3 In-practice circularity in the shipping industry 8
2.3.1 Ship Repair 8
2.3.2 Ship Recycling 9
2.4 Requests and initiatives in the sector 10
2.5 Stakeholders during the life cycle of maritime systems and components 10
2.6 Conclusion on circularity in shipbuilding 11

3 Circularity 13
3.1 Definition 13
3.1.1 Overview of frameworks 14
3.1.2 Conclusion of the definition of circularity 17
3.2 Measuring Circularity 17
3.2.1 Overview of methods 18
3.2.2 Conclusion on methods for measuring circularity 20
3.3 The Material Circularity Indicator 21
3.3.1 Overview of the method 21
3.3.2 Proposed adjustments to the MCI method 24

4 Design approaches 27
4.1 Design approaches in shipbuilding 27
4.1.1 Point-based design 27
4.1.2 Set-based design 28
4.1.3 Optimisation-based design 28
4.1.4 Systems-based design 28
4.1.5 Conclusion on ship design approaches 29
4.2 Systems Engineering 30
4.3 Ship design process at Damen Shipyards 31
4.4 Circular design approaches for consumer goods 32
4.4.1 Overview design approaches and strategies 32
4.4.2 Design approaches and the 10R Framework 32
4.4.3 Conclusion on design approaches for circularity 36

4.5 Differences in design strategies for shipbuilding and consumer goods 37
4.6 Conclusion on combining design approaches for circularity and ship design 38

5 Key indicators 39
5.1 Identifying key indicators 39
5.1.1 Material choice 39
5.1.2 Lifespan 40
5.1.3 Use frequency 41
5.1.4 Cost 41
5.1.5 Modularity 42
5.1.6 Reliability 42
5.1.7 Example of key indicators influencing design 42
5.2 Linking key indicators to the 10R framework 44
5.2.1 Design: Determining the design focus 44
5.2.2 Lifetime: Reuse and repair during functional lifetime 45
5.2.3 End of life: Refurbishment, Remanufacturing, Repurposing, Recycling and Recovery 46
5.3 Conclusion on key indicators 47

6 Application of the Circular Economy principles in Ship Design 49
6.1 Step 1: Identify the overall goal 50
6.1.1 General goal 50
6.1.2 Circular goal 50
6.1.3 Results after step 1 50
6.2 Step 2: Identify and breakdown system, sub-systems, components, sub-components and parts 51
6.2.1 Definition of System levels 51
6.2.2 System Boundaries 51
6.2.3 Functional, Logical and Physical architectures 52
6.2.4 Putting theory to practice 53
6.2.5 Results after step 2 53
6.3 Step 3: Determine the current level of circularity of existing design 53
6.3.1 Material Circularity Indicator 53
6.3.2 Acquiring information for the MCI 55
6.3.3 Results after step 3 56
6.4 Step 4: Map the system life cycle and associated stakeholders 57
6.4.1 Steps in the life cycle 57
6.4.2 Stakeholder analysis 58
6.4.3 Results after step 4 59
6.5 Step 5: (Re)design the system by use of the RFLP method, applying circularity principles 59
6.5.1 Requirements 60
6.5.2 Functions 62
6.5.3 Logical 62
6.5.4 Physical 62
6.5.5 Results after step 5 67
6.6 Step 6: Validate the (re)design 68
6.6.1 Validation Matrix 68
6.6.2 Measuring Circularity 69
6.6.3 Results after step 6 69

7 Case Study: The Wheelhouse 71
7.1 Step 1: Identifying the overall goal and mission 71
7.1.1 General goal 71
7.1.2 Circular goal 71
7.1.3 Continuation 71
7.2 Step 2: Identifying and breaking down the system, sub-systems, components, subcomponents and parts 72
7.2.1 System Boundaries 72

7.2.2 System levels . . . 72
7.3 Step 3: Determining the current circularity level . . . 78
7.3.1 Weight . . . 78
7.3.2 Gathering information . . . 80
7.3.3 MCI of the five sub-systems . . . 81
7.3.4 Conclusion on circularity . . . 82
7.4 Step 4: Mapping the system life cycles and associated stakeholders . . . 83
7.4.1 General life cycles and stakeholders of the five sub-systems . . . 83
7.4.2 life cycle and stakeholders of the floor . . . 84
7.5 Step 5: (Re)designing the system by use of RFLP method, applying circularity principles 85
7.5.1 Requirements . . . 85
7.5.2 Functions . . . 87
7.5.3 Logical . . . 87
7.5.4 Physical . . . 87
7.5.5 Variation of the RFLP's to look for alternatives . . . 90
7.6 Step 6: Validating the (re)design . . . 94
7.6.1 Validation Matrix . . . 94
7.6.2 Measuring circularity . . . 94
7.7 Review of the framework . . . 95

8 Discussion **97**
8.1 Scope effects . . . 97
8.2 Limitations . . . 97
8.3 Roadmap to implementation . . . 98
8.4 Recommendations . . . 99

9 Conclusion **101**

References **105**

A Appendix to chapter 3: The 12 principles of green engineering **112**

B Appendix to chapter 4 **114**
B.1 Taxonomy of design methods . . . 114
B.2 Den Hollander's theory on the design for preserving product integrity . . . 116

C System life-cycles with associated stakeholders **118**

D Case study **123**
D.1 MCI calculation for the wheelhouse . . . 123
D.2 Effort summary . . . 125

List of Figures

2.1 Circularity in all the phases of a vessel's lifetime (Sustainable Shipping Initiative and 2BHonest, 2021) . . . 6
2.2 The same hull but repurposed from support vessel to yacht . . . 8
2.3 Schematic representation of the processes and produced materials from ship dismantling and final destination of the removed materials (Calvalho et al., 2010) . . . 9
2.4 Recycled shipping capacity in Dead Weight Tonnage (Chao, 2020) . . . 10

3.1 Categorisation of linear and circular approaches for reducing resource use (Bocken et al., 2016) . . . 13
3.2 CE frameworks cited (wbcsd, 2018) . . . 14
3.3 This Butterfly diagram illustrates the way in which technological and biological nutrient-based products and materials circle through the system (Ellen McArthur Foundation, 2019). . . . 15
3.4 The 10R's . . . 16
3.5 The final set of themes and indicators (Boorsma et al., 2022) . . . 20
3.6 Diagrammatic representation of material flows (Goddin et al., 2019) . . . 22
3.7 Overview of the material streams for calculation of the MCI . . . 24
3.8 Visual of the material flows when combining the 10R framework with the MCI tool . . . 24
3.9 Visual of the material flows when combining the 10R framework with the MCI tool in symbols . . . 25

4.1 Evan's design spiral (Evans, 1959) . . . 27
4.2 Knowledge domains of the systems engineer and design specialist (Kossiakoff et al., 2011) 29
4.3 V model of the RFLP method created by Damen Shipyards (2018) . . . 31
4.4 Technical process of system analysis at Damen Shipyards (2022) . . . 31
4.5 Visual of the 10R model and design focusses based on Cramer (2019) . . . 33
4.6 The repurposing of a Nutella jar as a glass (Aguirre, 2010) . . . 36
4.7 The requirements pyramid (Ashby and Johnson, 2003) . . . 37

5.1 Disposal costs and prospects (Vezzoli and Manzini, 2008) . . . 41
5.2 Architectural view of modularity (Efatmaneshnik et al., 2020) . . . 42
5.3 Defining a product's purpose based on lifespan and frequency of wearing (H&M Group, 2021) . . . 43
5.4 Product purposes and their importance in the level of materials and design strategies (H&M Group, 2021) . . . 43

6.1 Visual of the framework for including the circular economy principles in the ship design approach . . . 49
6.2 Context diagram (Kossiakoff et al., 2011) . . . 52
6.3 Visualisation of a functional, logical and physical architecture, based on The Mathworks (2020) . . . 52
6.4 Visual of the meaning of a function, based on The Mathworks (2020) . . . 53
6.5 Overview of flows in the Material Circularity Indicator . . . 54
6.6 Overview of the 10R framework in combination with the MCI . . . 55
6.7 Standard steps in the life cycle of a ship (Damen Shipyards, 2023b) . . . 58
6.8 Overview of the RFLP method based on The Mathworks (2020) . . . 59
6.9 Spiral model of the system life cycle development (Kossiakoff et al., 2011) . . . 60
6.10 Example of a requirement breakdown structure (Reqtest, 2020) . . . 61
6.11 From Function to Physical solution mapping (Pahl et al., 2007) . . . 63

6.12 Example of a morphological chart representing eight-sub-functions and six sub-solutions (Börekçi, 2018) . . . 63
6.13 High-over process of physical selection and logical model creation (Vink, 2022) . . . 65
6.14 Circular Business Strategy Matrix (Atasu et al., 2021) . . . 67
6.15 A visualisation of the connections between the requirements, functions and physical system (Hopman, 2021) . . . 68
6.16 Product Management Map (PMM) (Kana, 2021) . . . 68
6.17 Legenda of the symbols used in the PMM (Kana, 2021) . . . 69

7.1 Visual of the RSD2513 (Damen Shipyards, 2023c) . . . 72
7.2 Logical and Physical Architecture of the Captain's Chair . . . 74
7.3 Visual of the two chair components; the seating chair and deck rail (Alu Design and Services AS, 2012) . . . 74
7.4 Logical and Physical Architecture of the Console . . . 75
7.5 Visual of the Console (Damen Shipyards Group, 2020) . . . 75
7.6 Logical and Physical Architecture of the Windows . . . 76
7.7 Visual of the Windows (Matterport, 2023) . . . 76
7.8 Logical and Physical Architecture of the Superstructure . . . 77
7.9 Visual of the Superstructure (Damen Shipyards Group, 2021) . . . 77
7.10 Logical and Physical Architecture of the Floor . . . 78
7.11 Visual of the floor. On in the upper figure the floor covering is shown and in the lower figure the floating floor is broken down in the different layers (Sika and Damen Shipyards, 2022). . . . 78
7.12 The fraction contribution of recycled material to current consumption (Ansys Granta Edupack, 2006) . . . 80
7.13 The stakeholders specifically for the current floor that is provided by Sika . . . 85
7.14 Requirement breakdown structure for the floor . . . 87
7.15 Functions breakdown structure for the floor . . . 88
7.16 Visual of the redesigned floor . . . 89
7.17 The requirements for the different alternative scenarios. The cross number indicates the expired requirement(s) for every scenario. . . . 91
7.18 The functions for the different alternative scenarios. The cross number indicates the expired function(s) for every scenario. . . . 91
7.19 Visuals of the physical solutions of the floor based on the requirements in alternative scenarios 2 and 3 . . . 93

8.1 Visual of the roadmap to implementation . . . 99

A.1 The 12 Principles of Green Engineering (McDonough et al., 2003) . . . 113

B.1 "Circular product design includes both design for preserving product integrity and design for recycling" (den Hollander, 2018). . . . 116
B.2 "A typology for design approaches for preserving product integrity in a circular economy" (den Hollander, 2018). . . . 116
B.3 3D design space for preserving product integrity (den Hollander, 2018) . . . 117
B.4 Example products plotted by den Hollander (2018). . . . 117

C.1 Stakeholders in the linear lifetime of a multiuser product . . . 119
C.2 Stakeholders in the linear lifetime of a unique product . . . 120
C.3 Stakeholders in the circular lifecycle of a multiuser product . . . 121
C.4 Stakeholders in the circular lifecycle of a unique product . . . 122

D.1 Effort of conducting the case study expressed in percentages of time spent on each step. 125
D.2 Effort of conducting the case study expressed in percentages of time spent on each step split out in activities per step. . . . 125

List of Tables

3.1 Overview of the required input per circularity measurement method 21

4.1 Overview of the design approaches for ship design 29

5.1 The influence of lifespan on the different R-levels 44
5.2 The influence of use frequency on different R-levels 45

7.1 The breakdown into components and parts of the sub-system ”Captain’s chair” 73
7.2 The breakdown into components and parts of the sub-system ”Consoles” 75
7.3 The breakdown into components and parts of the sub-system ”Windows” 76
7.4 The breakdown into components and parts of the sub-system ”Superstructure” 76
7.5 The breakdown into components and parts of the sub-system ”Floor” 77
7.6 The mass of the sub-systems 79
7.7 Morphological overview of the physical solutions matched with the functions 88
7.8 Morphological overviews for the different alternative designs, the number on the right indicates the function(s) that will not have to be fulfilled per scenario 92
7.9 Comparison of the designs on circularity, function and cost 94
7.10 Comparison in MCI level of the ”old” and ”new” floor design 94
7.11 Filled in Product Management Map for the redesigned floor 96

B.1 Taxonomy of DfX strategies based on Moreno et al. (2016) 115

D.1 Detailed overview for the MCI calculation of the five sub-systems 124

List of abbreviations

Abbreviation	Meaning
3DR	Design for Disassembly, Deconstruction and Resilence
C2C	Cradle to Cradle
CE	Circular Economy
CEDI	Circular Economy Design Index
CEI	Circular Economy Index
CE-TPC	Circular economy Transition in Product Chains
CTI	Circularity Transition Indicator
DFR	Design for Recycling
DfX	Design for Sustainability
DPM	Design Property Matrix
DWT	Dead Weight Tonnages
EEA	European Economic Area
EFRAG	European Financial Reporting Advisory Group
ESRS	European Sustainability Reporting Standard
EOL	End Of Life
EU	European Union
FFBD	Functional Flow Block Diagram
HKC	Hong Kong Convention
HVAC	Heating, Ventilation and Air Conditioning
IC	IHM Certificate
IHM	Inventory Hazardous Materials
IMO	International Maritime Organisation
ISO	International Organisation for Standardisation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LFI	Linear Flow Index
MCI	Material Circularity Indicator
NGO	Non-Governmental Organisation
NS	Nederlandse Spoorwegen
NAVAIS	New, Advanced and Value-added Innovative Ships
PLE	Product Life Extention
PMM	Product Management Map
QFD	Quality Function Deployment
ReSOLVE	Regenerate, Share, Optimise, Loop, Virtualise and Exchange
RPO	Retain Product Ownership
RFLP	Requirement-Functional-Logical-Physical
RSD	Reversed Stern Drive
SRR	Ship Recycling Regulation
TPE	Thermoplastic Elastomer
YETI	Yacht Environmental Transparency Index

List of symbols

Symbol	Definition	Unit
C_R	Fraction of mass of a product being collected to go into a recycling process	%
C_U	Fraction of mass of a product going into component reuse	%
$F(X)$	Utility factor built as a function of the utility X of a product	-
F_R	Fraction of a product's feedstock from recycled sources	%
F_U	Fraction of mass of a product's feedstock from reused sources	%
L	Actual average lifetime of a product	%
L_{av}	Average lifetime of an industry-average product of the same type	years
M	Mass of a product	kg
U	Actual average number of functional units achieved during the use phase of a product	functional units
U_{av}	Average number of function units achieved during the use phase of an industry average product of the same type	functional units
V	The mass of virgin material	kg
W_C	Mass of unrecoverable waste associated with a product	kg
W_F	Mass of unrecoverable waste generated during the process of recycling parts of a product	kg
W_O	The mass of unrecoverable waste through a product's material going into landfill, waste to energy and any other type of process where the materials are no longer recoverable	kg
X	Utility of a product	-

1
Introduction

In 2015, 193 world leaders agreed to 17 global goals to end extreme poverty, inequality and climate change by 2030. Goal number 12 states: ”Responsible consumption and production” (The Global Goals, 2015). The aim of this goal is to ensure sustainable consumption and production patterns. To achieve this goal, eleven targets have been set to create action. One of them being: ”Substantially reduce waste generation”. By 2030 the aim is to substantially reduce waste generation through prevention, reduction, recycling and reuse. In the maritime sector, a lot of (raw) materials are used for the construction of vessels which all have to be taken care of again at the end of a ship’s life. Ships are broken down at ship recycling yards, where loads of steel is recycled, but often with disregard for the environment. In 2018, 90.4% of the ships (measured in the gross tonnage) were recycled by shipbreaking and recycling industries in Bangladesh, India, and Pakistan. These are popular countries because of the absence of strict environmental regulations (Alam et al., 2019). Also, recycling is good but when looking at retaining value, recycling is not the best way and other methods such as reuse, or refurbishment are preferred (Cramer, 2020). Not only at the end of a ship’s life, during demolition, the materials need to be processed, but also during the ship’s lifetime of approximately 25 years systems on board are replaced, creating a lot of waste. Also, little is known about the way all other parts except for the steel of the hull are handled, such as electronic systems or furniture.

It could therefore be said that the shipping industry is currently an industry with a lot of waste where there are many opportunities to look into the implementation of a circular economy. In a Circular Economy (CE) there is no waste since waste is seen as a raw material for new products (Stahel, 2016). Taking into account the circularity of products when designing a vessel could reduce waste and improve the sustainability of vessels since up to 80% of a product’s environmental impact is determined already in the design phase (European Commission, 2020a). The circular economy principles, also known as cradle-to-cradle, are therefore seen as a sustainable strategy.

Damen is a shipbuilding company that has been designing and building ships since 1927. It is Damen’s ambition to be the most sustainable and digital maritime solutions provider. Their future is emission-free and connected. The goal is to build the ships cradle-to-cradle and operate them emission-free. To reach this ambition, the sustainability roadmap has been defined. The Damen Sustainability Roadmap consists of three pillars; Sustainable Organisation, Sustainable Operation and Sustainable Design. The pillar Sustainable Design consists of three sub pillars; Zero emissions, Cradle-to-cradle and Innovations. It’s for this reason that Damen is exploring how to include this cradle-to-cradle or circular economy thinking in the design process of the vessels.

1.1. Problem definition

At the moment, Damen designs ships with a focus on functionality, cost and operability. There is not yet a specific approach to include circularity in the designs. Therefore, Damen Shipyards would like to create a clear design process, design guidelines and tooling to take this important topic into account for future designs, such as the design for a wheelhouse.

The goal is to develop a method to take circularity into account during the ship design process. This is done by first assessing the current level of circularity in the maritime sector. Next, it is important to select a definition of circularity and a way to measure it. After that, the goal is to identify important system properties, for example, lifetime, cost, level of usage, etc., and be able to identify the level of circularity that is currently prioritised in the design of the system by looking at these system properties. Combining these topics, a framework will be drafted to guide future ship designers in also taking circularity into account next to the current design drivers such as functionality, cost and operability. As a case study, the framework will be tested on the wheelhouse of a Damen RSD2513 tug. In the case study, different system levels will be examined on their current circularity level and improvements to increase the circularity level will be proposed.

1.2. Research questions

The problem definition can be translated into the following research question:

How can circularity be taken into account in the ship design process and improved by linking product characteristics to circularity indicators?

In order to systematically answer the main research question, multiple sub-questions are proposed. These sub-questions will need to be answered before answering the main question.

1. To what extent and in which way is circularity at this moment present in the shipbuilding industry?
2. How to achieve circularity?
   - How is circularity defined?
   - How can circularity be measured?
3. What is the best design approach to address circularity in ship design?
   - What are the design approaches for shipbuilding?
   - What are the circular design approaches for consumer goods?
   - What is the difference between design approaches for consumer goods and ship systems?
4. How do key indicators influence the circularity level of a system?
   - What are the key indicators of a system to evaluate the current focus level of circularity?
   - What is the influence of the key indicators on the different circularity levels?
5. What is the impact of including circularity in the ship design approach?

   Case study:
6. How to improve the level of circularity in a wheelhouse?
   - What are the systems that need to be taken into account when assessing a wheelhouse on circularity?
   - What is the current level of circularity of these systems?
   - Until what level of circularity is improvement possible on these systems?
   - What is the cost of improving the circularity of these systems?
   - Does the developed framework fit the purpose?

1.3. Scope

This research will focus on providing insight into the material and component choice when designing a new vessel, by linking system properties to circularity indicators. It will provide a guide for future designers on how to use certain product properties to improve the circularity of maritime systems. Next to circularity, there are other aspects that play a vital role in stating whether or not a product might be sustainable. Examples of such aspects are the impact on the environment by water pollution, land degradation, influence on climate change, etc. The scope of this research will focus purely on circularity, not on the other (environmental) footprints a product might have.

Even though the influence of a designer is mostly at the start of a product's lifetime, this does not mean a designer cannot have any influence during a product's lifetime. Therefore the whole lifetime of a system will be assessed in this study and all these phases will be taken into account during the design phase, in order to influence them. An example can be that the designer does not have a say in whether a product will be recycled or not. However, a designer can design a product out of certain materials and in such a way that recycling is possible by creating a product in which different material types can be easily separated.

1.4. Structure

To start, literature research was conducted to provide insight, gain knowledge about the subject and define the research gap. In chapter 2, research will be done into the applications of circularity in the shipbuilding industry at this moment and it will be evaluated whether these applications are up to date and what aspects are missing. Next, deeper research into different frameworks on the definition of circular will be performed and different methods on how to measure circularity will be set out. Out of these, one definition and one measurement method will be chosen to continue the research. These results are presented in chapter 3 In chapter 4, design approaches for circular products and design approaches for ship design will both be reviewed. After this, the difference between the maritime industry design methods and other industries such as consumer products will be reviewed. This will lead to an insight into the important system properties that have a relation to circularity and an overview is created to map and connect these properties to circularity indicators in chapter 5. A framework is then drafted in chapter 6 that provides a guide for ship designers to take the circular economy principles into account, with the use of key indicators. In chapter 7, the wheelhouse of an RSD2513 is used as a case study. To do so, the important elements of a wheelhouse will be evaluated and examined on their current properties and functions to look at the current level of circularity. After this, adjustments for the systems will be proposed to increase the circularity of the system. The cost will also be calculated for these adjustments. To review this research, a discussion is presented in chapter 8 and finally a conclusion will be drawn in chapter 9.

1.5. Literature research

The Chapters 2, 3, 4 and part of chapter 5 were part of a literature study. By first identifying the current practice of the implementation of the circularity levels in the shipping industry, gaps were identified. After this, the definition of circularity and measurement methods were researched. Next, the ship design and circular design approaches were identified and finally, a closer look was taken at indicators defining the circularity of a system. This was all done by the use of the databases of Scopus, WorldCat, the TU Delft repository and Google Scholar. To achieve relevant results, search terms were determined in advance. The keywords that were determined were: ”Circular Shipping”, ”Circularity definition”, ”Circular Frameworks”, ”Measuring Circularity”, ”Ship design approach”, ”Circular design approach”, ”Circularity regulations”, and ”Circular ship design”. Due to the huge amount of literature on circularity, a selection had to be made of the search results. Search criteria were introduced to limit the information to the most relevant parts. These criteria include publication data and document or source type, also literature after 2000 was preferred. The results were scanned based on the keywords and abstracts and often the reference lists from the results led to more relevant documents. Next to that, in-house documents at Damen Shipyards were used to get information on the common practise there. The information found during the literature study was eventually used for the creation of the framework and the execution of the case study.

2 Current applications of circularity in shipbuilding

In this chapter, the aim is to answer the first research question; *To what extent and in which way is circularity at this moment present in the shipbuilding industry?* To answer this question, the current practice of circularity in the shipbuilding industry will be set out. This section will be subdivided into five sections. First, academic research into circularity in the shipbuilding industry will be set out. Then the rules and regulations in the shipping industry that involve circularity are addressed. Thirdly, the current, in-practice level of circularity in the shipping industry will be discussed. After that, the initiatives and requests from the sector will be set out and finally, the stakeholders during the life cycle of maritime systems will be set out to see where changes can be made.

2.1. Previous research

Regarding the research into the impact of ships and shipbuilding on the environment, there have been some different research activities. First of all, Cozijnsen (2019) has defined a framework for the Yacht Environmental Transparency Index (YETI). The aim of the YETI is to assess a yacht's environmental impact over its life span. Different steps in the lifespan are considered such as the yacht getting built, and after that, maintenance taking place every 2.5 years. The maintenance consists of a docking period during which the paint and hull protection system is updated. This goes on for 20 years after which the yacht requires a major refit. Because the work of such a refit is significant and the depreciation of the yacht indicates that the end-of-life value is reached at 20 years, 20 years is taken as the end-of-life moment. To define this framework, Fast Track Life Cycle Analysis (LCA) methodology is used, which is the quantification of materials and is applied to find the impact of the yacht on the environment. This research into the production of a yacht mostly covers materials used within a yacht, not taking into account the environmental impacts of business processes. Following up on this research, Ettema (2021) has mapped and aimed to reduce, the environmental impact of leading business processes in the yacht building industry. Focusing mostly on the impacts of the yacht-building process and the potential for innovation in this area. Even though both of these researches focus on the whole life cycle of a vessel, circularity was not the main focus.

With a focus more on circularity, Veenstra et al. (2018) performed a CEDI-index validation for the circular fishing vessel design process. Where CEDI stands for The Circular Economy Design Index. With the CEDI design approach, three crucial Circular Economy factors are holistically combined. The three factors are decarbonisation, recycling and fish processing automation.

Razmjooei et al. (2023) have performed a bibliometric analysis of the literature on circular economy and sustainability in maritime studies. They state that many academics, practitioners and policy-makers have focused on the notion of circular economy as a way to operationalise sustainable development, but that there is a shortage of review studies that review the evolution and status of CE with respect to sustainability in the maritime industry.

Recently, R. Joensuu et al. (2023) have released a white paper about the potential impact which remanufacturing could have on the maritime sector. Remanufacturing involves the process of making a product as new from a second-hand product. This is done by disassembling, checking, cleaning, and when necessary, replacing or repairing components of a product. For a company to actually engage in remanufacturing is often said to be difficult, because it's hard for companies to predict the number and the timing of products that could return from the market. Also, the quality of the products that return from the market differs, complicates diagnostics and comes at a cost. Several pieces such as pumps, engine blocks, rudder stocks, etc. are listed to have the potential for remanufacturing, saving cost, energy and emissions compared to manufacturing. To apply remanufacturing, the logistics for part supply and hubs for recollection would need to be set up. Also, policies and certifications regarding this subject are missing. Lastly, skill development and knowledge building are very important for the equipment manufacturers.

Finally, relevant research into circularity was published in 2021 by the Sustainable Shipping Initiative and 2BHonest. The research explored the opportunities and barriers to increasing circularity in the shipping industry. Sustainable Shipping Initiative and 2BHonest (2021) concluded three things: "1) The accelerating trends and patterns in both shipping and ship recycling set the scene for a transition to a circular shipping industry. 2) Circular economy principles should be built into every stage of the ship life cycle - from design to construction; to operations and recycling. 3) Global regulation and multi-stakeholder collaboration are essential to realise the transition to a circular shipping industry." (Sustainable Shipping Initiative and 2BHonest, 2021) The actions of building in the circular economy principles into every stage of the ship's life cycle are shown in Figure 2.1. Regarding the third conclusion of global regulation, the next section will explain more regarding current regulations.

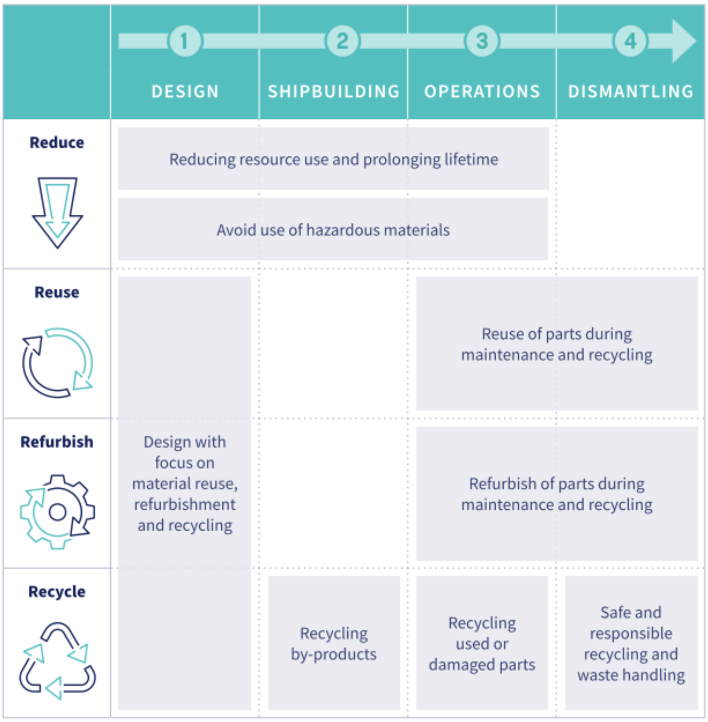


Figure 2.1: Circularity in all the phases of a vessel's lifetime (Sustainable Shipping Initiative and 2BHonest, 2021)

Similar research has been done by both the Maritime Sisters and Blue City (2023) for the Dutch maritime industry and Circular Shipping Initivative (2018) with a light focus on the Danish maritime industry. Maritime Sisters and Blue City (2023) conclude that where is willingness to implement the circular principles in the industry, but there are some challenges such as knowledge, means, traceability and law. The Circular Shipping Initivative (2018) conclude that digitisation will help to shift the maritime industry to more sustainable practices. The circular economy will require strategic partnerships across industries but is a key enable for change. By digitisation of global supply chains, new markets can be identified and commercialised. This can lead ship owners to rethink their role in the development of a global circular supply chain.

2.2. Regulations

In this section the first sub-question will be answered; *What are the regulations with regard to circularity in shipbuilding?*. In 2009, the International Maritime Organisation (IMO) developed and adopted The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships. Also referred to as the Hong Kong Convention (HKC) (IMO, 2015). The convention is aimed at making sure that ships that have reached the end of their lifetime and need to be recycled, will not pose any unnecessary risks to human health, safety and the environment. Before the ship can be recycled, an inventory of hazardous materials will need to be carried out. After this, the ship recycling yard needs to come up with a recycling plan. To put the convention into force, 15 States, which represent forty per cent of the world merchant shipping by gross tonnage, and their combined maximum annual ship recycling volume should not be less than three per cent of their combined tonnage have to sign it. During the process of this research, the requirements to put the convention into force were met and on June 26th 2025, the convention will enter into force (IMO, 2023).

Another important regulation regarding ship recycling is the European Union Ship Recycling Regulation (EU SRR). This regulation requires all large sea-going vessels which sail under an EU Member State Flag to use an approved ship recycling facility included in the European list. The regulation has been put in place since 31 December 2018. 35% of the world's fleet is owned by Europeans and the European list of recycling facilities contains 41 yards. This equals a recycling capacity of nearly 2.85Mi Light Displacement Tonnes (European Commission, 2020b). The EU SRR is aimed at providing early ratification of the Hong Kong Convention within both the European Union and in third countries by applying proportionate controls to ships and ship recycling facilities on the basis of the Hong Kong Convention (European Union, 2013). Part of both the EU SRR and the HKC is the Inventory of Hazardous Materials (IHM). "Ships flying the flag of an EU/EEA member state are required to have on board an IHM Certificate (IC) issued on behalf of the flag, starting from 31 December 2018" (DNV, n.d.). This only holds for ships over 500 gross tonnage. Examples of hazardous substances are asbestos, heavy metals, hydrocarbons, ozone-depleting substances and others.

Next to the recycling rules specifically focused on the maritime sector, the European Commission has also drafted a Circular Economy Action Plan which provides a future-oriented agenda to achieve a more competitive and cleaner Europe in co-creation with economic actors, consumers, citizens and social organisations. The plan has been implemented since 2015 and aims to accelerate the change needed to comply with the European Green Deal whilst also building on circular economy action. In this plan there are no specific actions listed for the maritime industry but presents a set of initiatives, focused on seven key product value chains to develop sustainable products, services and business models without waste (European Commission, 2020a).

Additionally, by order of the EU, the European Financial Reporting Advisory Group (EFRAG) has developed the European Sustainability Reporting Standard (ESRS) divided into five subjects of which one, E5, addresses "Resource use and circular economy" (EFRAG, 2022). The standard has been adopted end of July 2023 and the reporting requirements will be phased in over time for different companies. The aim of the standard is to give users of sustainability statements insight into how the undertaking affects resource use, the actions that have been taken towards circularity, the current plans and capacity to adapt the business in line with circularity principles, the risk associated with that, and the financial effects of it (EFRAG, 2022). Six disclosure requirements have been drafted, For every disclosure requirement, the undertaking has to disclose information regarding the requirements:

- E5-1 Policies related to resource use and circular economy
- E5-2 Actions and resources related to resource use and circular economy
- E5-3 Targets related to resource use and circular economy
- E5-4 Resource inflows
- E5-5 Resource outflow
- E5-6 Potential financial effects from resource use and circular economy-related impacts, risks and opportunities

By using the disclosure requirements, the company will draft a report addressing all topics and will get insight into resource inflows, outflows and waste. This report will then be audited by an independent, authorised institution.

The International Organisation for Standardisation (ISO) is an independent, non-governmental international standard development organisation. At this moment, the ISO is developing multiple standards with regard to a circular economy. The ISO WD 59 004 will be the main standard aiming to give a common understanding of a circular cconomy explaining terminology, principles and a framework for implementation. Under this "main" standard, there will be three more specific standards. There will be the ISO WD 59 010 which will provide a guideline to transformer business models from linear to circular, the ISO WD 59020 to provide a framework on how to measure and assess circularity performance, and the ISO NWP 59 040 to provide a further framework and toolbox for reporting circularity performance at the product level. Lastly, added to this there will be two supporting documents, the ISO TR 59 031 standardising performance-based approaches for a circular economy, and ISO TR 59 032 which contains a review of business model implementation (Balder, 2021). The release date of the ISO norm is not known yet, but when the norm is released this can be a helpful way of universally defining circularity for all users.

2.3. In-practice circularity in the shipping industry

Even though circularity is not (yet) a very hot topic in the shipping industry, the circular economy principles are already applied more than one might think. However, they are often not applied because companies wish to be circular, but often repair of maritime components is simply cheaper than replacement, letting cost be the leading factor instead of the environmental considerations. It is not uncommon for a shipping company to sell vessels second-hand to maintain a young fleet, whilst others operate many second-hand ships (Sustainable Shipping Initiative and 2BHonest, 2021). The value retentions of ship repair and ship recycling will be further elaborated upon in this section.

The three most common value-retaining circular economy principles present in the maritime sector are the reuse of vessels, ship repair and ship recycling (Sustainable Shipping Initiative and 2BHonest, 2021). Another practice, especially common in the yachting industry, is refitting vessels (Cozijnsen, 2019). A refit could be seen as a refurbishment of the existing yacht. Another example of reusing a vessel but in another function, so re-purposing, is the conversion of ships. A good example here is the motor yacht Ragnar, which used to be known under the name Sanaborg and was built as an ice-breaking multi-purpose support supply vessel. The result of the conversion is shown in Figure 2.2.

(a) Sanaborg (Boat International, n.d.)

(b) Ragnar (Icon Yachts, n.d.)

Figure 2.2: The same hull but repurposed from support vessel to yacht

The circularity of vessels and equipment is at this moment also limited by class regulations. Rules for example imply a CO_2 reduction of 80% by 2050 (compared to 2020) (Maritime Sisters and Blue City, 2023). This means that that current engines can not be endlessly reused in the future due to these type of emission requirements. Next to that, vessels have to comply with more rules and stricter inspection, the older they get (Bureau Veritas, 2023). Making it harder for old ships to still be compliant with class and making it attractive for the vessels owner to eventually sell the vessel for dismantling. Repair and recycling of vessels however is common practice, these two will now be further elaborated upon.

2.3.1. Ship Repair

Regular inspections are an obligation from class societies. During these surveys, the ship needs to be in good condition and fit for the purpose the ship is intended for (Lloyd's Register, 2022). Also the ship will need to be docked to fulfil the docking survey, providing a good opportunity to maintain the underwater hull. Yards where ships can be docked are often referred to as ship repair yards (Mikelis, 2019). During these big maintenance moments, repairs are performed. But also in between surveys, reparations are performed on board (Senturk, 2011). Systems on board ships are often high-value, making them economically attractive for repair, since the repair of parts is often cheaper than replacing the whole system. Additionally, from a logistics point of view repair is also very important. A good example is the ship's engine. The engine is the driving force of the vessel, located low in the ship. Complete replacement of a broken engine would cost a lot of time, effort and money, whilst repair of smaller parts is easier and cheaper.

2.3.2. Ship Recycling

Ship recycling is the term used to refer to ship breaking or ship dismantling (Alam et al., 2019). In the process, marine vessels are deconstructed, and reusable and recyclable materials are decoupled. Most ships are dismantled in Bangladesh, India and Pakistan. In 2018, 90.4% of the vessels, measured in gross tonnage, were dismantled in one of these three countries. This is done because of the cheap labour, government support, high demand for recovered materials from ships, and above all, the absence of strict environmental regulations. This all results in a higher scrap value for the owner of the vessel, where the values in Pakistan, India and Bangladesh are often twice as high as in Europe (GMS, 2023). Due to the absence of environmental regulations, open beaching comes with the uncontrolled release of hazardous wastes (Alam et al., 2019). The political concerns regarding ships dismantling in Europe are high, but only 3% of the ships are dismantled on European yards. A schematic representation of the processes of ship recycling is shown in Figure 2.3.

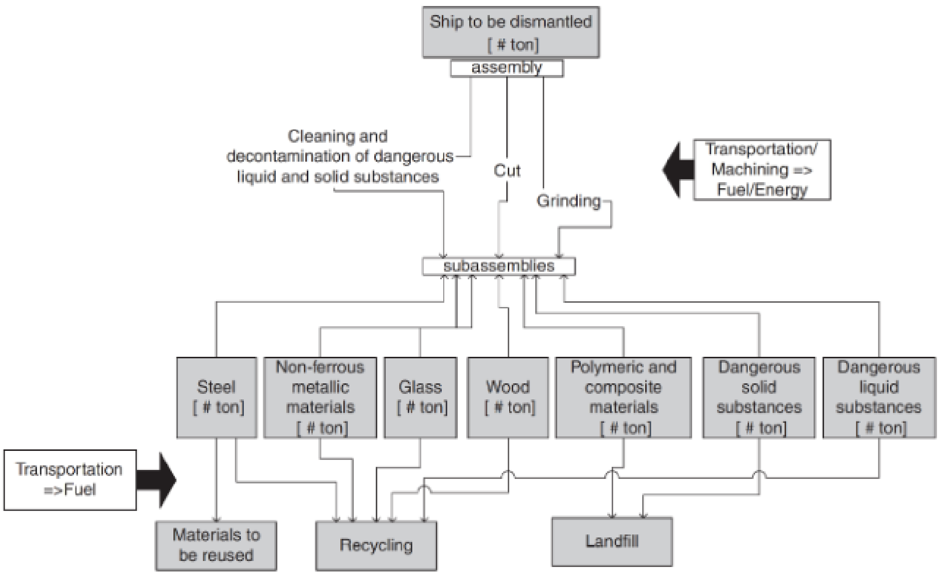


Figure 2.3: Schematic representation of the processes and produced materials from ship dismantling and final destination of the removed materials (Calvalho et al., 2010)

Approximately 50% (up to 1.5 m tons) of the national steel production in Bangladesh consists of recycled ship-breaking steel. In Pakistan, this is about 15% (up to 800,000 tons) and for India 5-6 % of the steel needs are satisfied by recycled steel from ships. The steel is either reheated and re-rolled or melted down and re-processed. Shipbreakers in Chittagong state that approximately 85% of a ship is recyclable steel where 75% is re-rollable steel and 10% can be seen as melting scrap. Even though this could be seen as a good example of circularity in shipbuilding, the environmental impact and occupational safety in these countries face great challenges (Chao, 2020) (Sarraf et al., 2010). The total recycled shipping capacity in Dead Weight Tonnages (DWT) is shown in Figure 2.4. Unfortunately, due to the lack of regulations, yards do not map or publish the purpose of other components on board besides the steel, making it hard, if not impossible, to map the destiny of these materials.

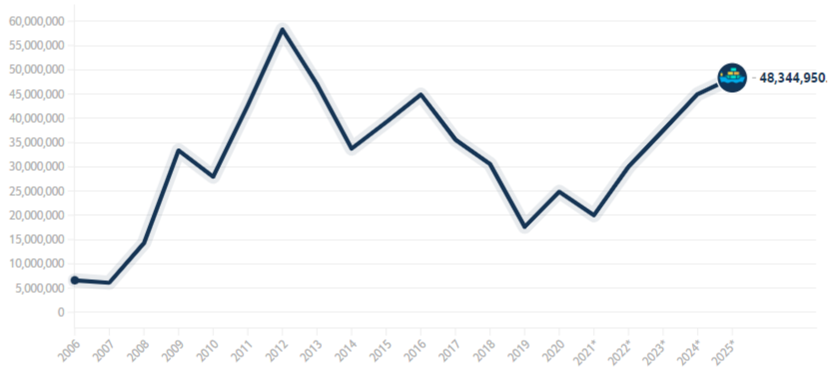


Figure 2.4: Recycled shipping capacity in Dead Weight Tonnage (Chao, 2020)

2.4. Requests and initiatives in the sector

More and more maritime companies are including sustainability and circularity in their policies and goals. Fincantieri for example, has the goal to ”reduce environmental impact and promote the development of a circular economy” (Fincantieri, 2021). The practical part of this ambition was the signing of an agreement with ArcelorMittal and Paul Wurth Italia in 2021 to reconverse the full production cycle of Taranto steelworks by the use of environmentally friendly technologies. Another example of a circular economy initiative is the Cradle to Cradle Passport developed by Maersk Line. The goal of the passport is to gain greater control over the materials used by Maersk, with the ultimate goal of making new ships from old (Ellen MacArthur Foundation, n.d.).

Also, Damen Shipyards is getting more and more requests from clients to include circularity in their vessels (Damen Shipyards, 2023a). A Dutch port for example wishes to have sustainable and circular materials in its patrol vessels. A city ferry service asks about the origin of materials and their circularity and a company operation on the offshore wind market demands to have information regarding the IHM and scrappage expectations to facilitate safe and environmentally sound recycling.

Recently, Damen has reviewed the level of circularity of their electric tug, Sparky. It turned out that it is very hard to get information from suppliers about their level of circularity whilst it is very important in the move towards fully circular vessels (Collier, 2023). To map the sustainability of their suppliers, Damen Shipyards uses a platform called ”Integrity Next”. Via this platform, Damen asks their suppliers questions on the Environmental, Social and Governance (ESG) sustainability levels. Unfortunately, circularity is not included in these questions, except for the mapping of hazardous materials. When sending out the questions, it turned out that the suppliers are really willing to help in mapping their progress on the ESG aspects, also because Damen is one of their biggest clients. Therefore the expectation is that if Damen asks for circular systems and products, suppliers would be willing to look for circular options (L. Wilming, personal communication, May 15, 2023).

2.5. Stakeholders during the life cycle of maritime systems and components

To make changes, it’s important to identify the stakeholders during the life cycle of maritime systems. Stakeholders are important since they determine how the product/vessel will be used and thus where circularity might play a role during the lifetime of the product. Furthermore, stakeholders will determine when the lifetime of the vessel will end. Looking at the life cycle of a vessel, several steps can be distinguished and in every stage, different stakeholders play a role.

- Design phase: Ship design company
- At the start/throughout lifetime: Financial parties
- Material distraction, transportation, basic product production and distribution: Sub-contractors/System Suppliers
- Ship production: Shipbuilding yard
- Operation: Customer/operating party
- Maintenance/repair: Customer and repair yard

- Decommissioning: Ship recycling yard
- Throughout the lifetime: Classification societies and Flag state

The focus of this research is on the design phase. When designing for circularity, it is important to already consider the whole life cycle of a system including its stakeholders to make sure that materials and knowledge are kept in the loop. The ship design company that has to consider the whole life cycle can be either an independent company or the company that will build the vessel. At Damen Shipyards, the vessels are designed and built in-house. Most of the design is determined by requirements set by the client. As mentioned before, more and more clients are asking Damen about circular vessels with for example circular interiors (Damen Shipyards, 2023a).

To finance a vessel, vessel owners, but also shipbuilding yards, often use financing from parties like banks or ship financing institutions. To get financing, applicants have to submit the plan for the vessel. These plans include expected return, deployment of the ship, company and management. A bank or financing institution has acceptance criteria and restrictions on the loans and financing which depend on ship type (Nesec, n.d.). One of the criteria can be circularity or sustainability in general. When a vessel is designed with a focus on circularity or sustainability is financed, this can then also be sold to the investors of the bank or financing institution as a sustainable investment (P.P. Nota, personal communication, April 26, 2023).

To construct a ship, many of the systems and materials on board are supplied by external suppliers. This means that designers are often dependent on the options suppliers offer. If there are no suppliers offering circular options for the chairs on board, it will be hard for the designers to create a fully circular cinema room. Therefore it is important to be in good contact with the suppliers, especially with the growing interest and demand for circularity.

During operation, the customer that bought the vessel is often the user of the vessel. It also happens that the ship operator is not the ship owner since a vessel might be leased. Then often the leasing party is responsible for the vessel during operation. During this phase, often small repairs on board are carried out by the crew during sailing time.

Depending on the ship type, maintenance is done either by the yard that produced the vessel or by another repair yard. There are strict rules regarding vessel maintenance. There are annual surveys that have to be carried out every year. These surveys consist of visual inspection and measurements which are all done on board (Lloyd's Register, 2022). Intermediate surveys are mandatory to perform instead of the second or third annual survey. This survey is often performed in a dry dock. Since there is a similar timeline for docking surveys, the two surveys are often combined. During the survey the ship needs to be in "a satisfactory condition and fit for the service for which the ship is intended" (Lloyd's Register, 2022). Finally, there is the special survey, also called the renewal survey, that has to take place once every five years. "The renewal survey should consist of an inspection, with tests when necessary, of the structure, machinery and equipment to ensure that the requirements relevant to the particular certificate are complied with and that they are in a satisfactory condition and are fit for the service for which the ship is intended" (Lloyd's Register, 2022).

As was already stated in subsection 2.3.2, the recycling of the ships is done at ship recycling yards, often located in countries such as Bangladesh, India and Pakistan. In these countries labour is cheap and regulations are absent. Even though the end of life is a very important step in the life cycle of a vessel, due to the absence of regulations in the leading countries, there is little control over this phase.

The classification societies and flag states are the authorities drafting regulations for the conditions of the systems and vessels. Classification societies demand regular surveys but also during design and construction, many regulations apply to vessels and their systems. The flag states determine the conditions for the recycling of ships and therefore play an important role in the implication of circularity. Although a flag state can make its own policies, it always has to comply with the IMO rules and regulations (IMO, 2015).

2.6. Conclusion on circularity in shipbuilding

Even though it might be unconscious, it can be concluded that during the operational phase, the shipping industry is already quite circular. However, the focus is mostly on the principles of reuse, repair and recycling, whilst other circular economy principles also have the potential to be included. Additionally, many regulations are put into place regarding circularity and companies are becoming more and more aware. However, enforcing these regulations is harder. The EU SRR for example would improve circularity in a great way, but a lot of ships are not sailing under European flags, circumventing this regulation. The fact that the HKC took almost 14 years to be signed by enough states, shows that many states are also not very eager to comply with the regulations that would improve circularity, most likely because of the cost and extra work that will come with it. Also, about the recycling of the steel of ships, quite a lot is known since this is, in weight, the biggest part of the vessel and relatively easy to recycle. But unfortunately little is known about the way the rest of the vessel is discarded. However, during the design phase, circularity is not yet something that is considered and often materials with the best price/quality rate are chosen instead of recycled materials. Initiatives such as the Cradle to Cradle Passport can improve the (re)use of recycled, refurbished or remanufactured materials and components. By looking at the stakeholders during the life cycle of vessels and maritime systems, it can be concluded that many stakeholders play a role and it will be hard to influence all of these stakeholders. Instead of selling a design, a design company could also be the owner of the shipbuilding yard, and if the vessel is leased instead of sold, then the same company that designed and built the vessel can be in charge of the decisions regarding repair, maintenance and in the end recycling. However, this is in practice not the case, so to get the maritime economy circular, the CE principles should be built into every stage of the ship's life cycle. Design is the start of every life cycle and during this phase 80% of a product's environmental impact is determined (European Commission, 2020b). To start including circularity in the design phase, a framework for achieving circularity and a way to measure it will be selected in the next chapter.

3 Circularity

Now that the gap in the current maritime sector has been identified with regard to circularity, this chapter aims to find an answer to the second sub-question: ”*How to achieve Circularity?*” To do this, two sub-sub-questions will be answered. First of all, the definition of circularity will be stated and various frameworks will be set out to, in the end, choose one framework to continue this research. Secondly, different ways of measuring circularity will explored of which one will be selected to continue the research.

3.1. Definition

In this section the first sub-question will be answered; *How is circularity defined?*. The current 'take-make-dispose' economy is a linear model (Di Maio and Rem, 2015) (Bocken et al., 2016). In the linear economy, the life cycle of a product starts by extracting raw materials and acquisition. Then materials are processed and manufactured. After that, the steps are material transportation, product fabrication, transportation, distribution, operation, consumption, maintenance, repair and finally product disposal/scrapping (Shama, 2005).

Stahel (2016) describes the linear economy as a flowing river, whilst the circular economy can be seen as a lake, where the goods and materials are reprocessed. Di Maio and Rem (2015) state that in Circular Economy (CE) models, products maintain their added value for as long as possible and minimise waste. The aim is to keep resources within the economy when products no longer serve their functions so that materials can be used again and therefore generate more value. Thus circular business models create more value from each unit of resource than traditional linear models. So recycling plays, along with reuse and refurbishing/re-manufacturing an important role within the circular economy model. Therefore it is often considered a cornerstone of a broader vision for the sustainability of a closed-loop society (Gutowski et al., 2013).

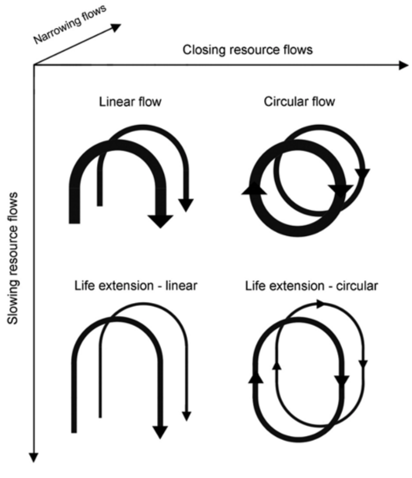


Figure 3.1: Categorisation of linear and circular approaches for reducing resource use (Bocken et al., 2016)

The circular approach contrasts with the traditional linear business model of production of take-make-use-dispose and an industrial system largely reliant on fossil fuels. This is because the aim of the business shifts from generating profits from selling artefacts, to generating profits from the flow of materials and products over time (C. Bakker, den Hollander, et al., 2014).

Bocken et al. (2016) have introduced two fundamental strategies toward the cycling of resources:

- Slowing resource loops: Through the design of long-life goods and product-life extension, the utilisation period of products is extended and/or intensified, resulting in a slowdown of the flow of resources.
- Closing resource loops: Through recycling, the loop between post-use and production is closed, resulting in a circular flow of resources.

These two approaches are distinct from a third approach toward reducing resource flows:

- Resource efficiency or narrowing resource flows, aimed at using fewer resources per product.

Resource efficiency is not aimed at the cyclic use of products and materials, but an approach to reduce resource use associated with the product and production process presented as an eco-efficient cradle-to-grave material flow. The strategies are visualised in Figure 3.1.

For each goal, different design strategies are required. For example, when designing for product-life extension, the ease of maintenance and repair is very important, next to the design for upgradability and adaptability, and the design for dis- and reassembly. When designing for closed loops, thus circularity, one needs to take into account design for a technological cycle, design for a biological cycle and design for dis- and reassembly (Bocken et al., 2016).

The World Business Council for Sustainable Development (WBCSD) conducted research into the use of CE frameworks by interviewing 39 companies and additionally 8 NGOs, governments and academia (wbcsd, 2018). This included 18 Factor10 members, which is a platform consisting of more than thirty companies from around the globe which are committed to the circular economy (wbcsd, n.d.-b). Next to that, 140 annual reports and 25 other relevant sources were reviewed. It was concluded that most companies have their own definition of the circular economy. After this, the butterfly diagram by the Ellen MacArthur Foundation was the most referenced framework. Other frameworks were also mentioned, of which the distribution is shown in Figure 3.2. The wbcsb researchers conclude that this indicates that companies are moulding and defining circularity in ways that are most relevant to their core business because the concept of the circular economy is relatively vague and amorphous. Therefore, in the next sub-sections, various definitions and frameworks on the scope of circularity will be discussed.

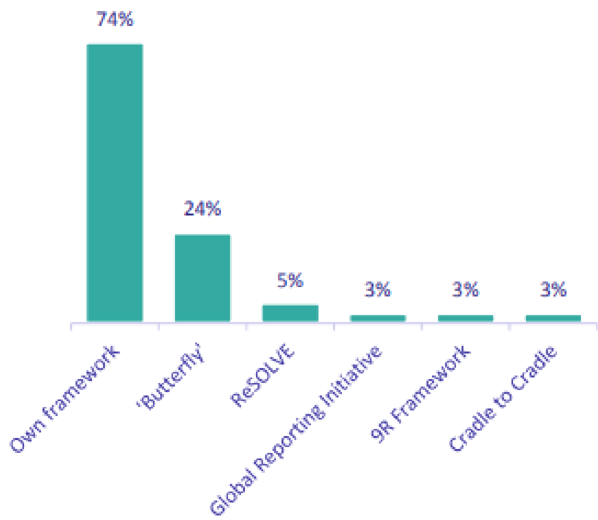


Figure 3.2: CE frameworks cited (wbcsd, 2018)

3.1.1. Overview of frameworks

In this sub-section, four different frameworks on the definition of circularity will be set out. These are not all frameworks represented in literature, but a collection of the most commonly used and known definitions, also based on Figure 3.2.

'Butterfly'

The circular economy system diagram, known as the butterfly diagram, illustrates the continuous flow of materials in a circular economy as can be seen in Figure 3.3. There are two main cycles: the technical cycle (right side) and the biological cycle (left side). In the technical cycle, products and materials are kept in circulation through processes such as reuse, repair, re-manufacture and recycling. If the right wing, the technological cycle, were three-dimensional, it could represent a cone in relief, or a mountain, with maintenance circling around the top of the hierarchy, recycling around the bottom and value upgrades in between (C. Bakker, den Hollander, et al., 2014). In the biological cycle, the nutrients from biodegradable materials are returned to the earth to regenerate nature (Ellen McArthur Foundation, 2019).

From this diagram, it can be concluded that the goal for designers and product users should be to stay withing the smallest circular loop possible. Next to that, the loss of value from the top to the lower circles should be minimised, or even be negative so the value will increase (C. Bakker, den Hollander, et al., 2014). When a product needs to be taken out of service, there are often two options: up-cycle or down-cycle the product. Up-cycling is a strategy that reuses a product in a way that holds more value than the original product, whereas down-cycling reuses a product in a way that holds less value than the original product (Ritchie and Freed, 2021). This value does not need to be seen as cost value but is the perception of value, such as artistic value or environmental value (Wegener, 2016). For the circular economy, the goal is to maximise a product's value at each point in a product's lifetime (Stahel, 2016).

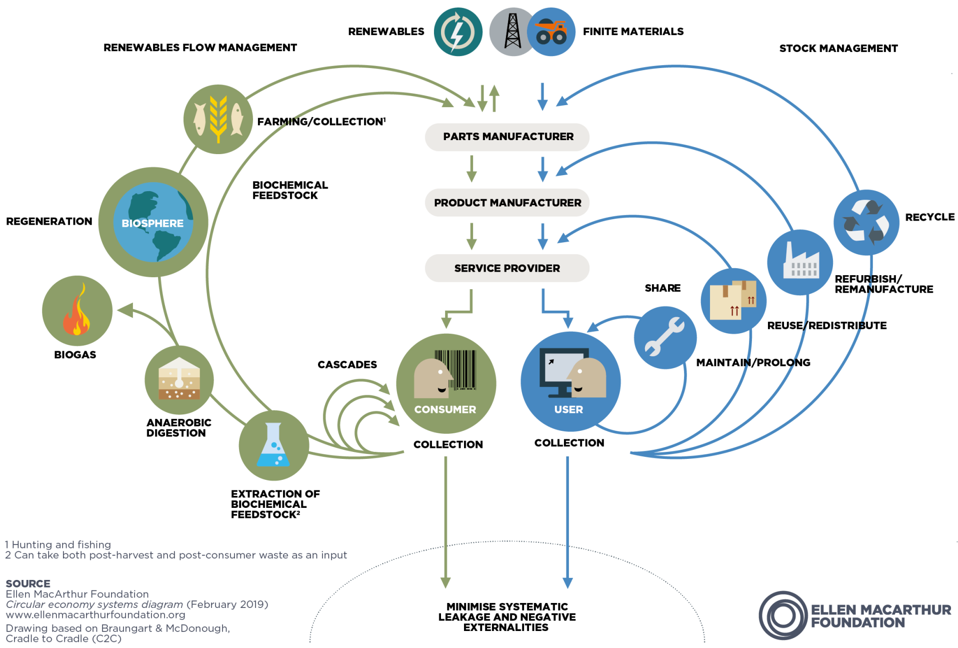


Figure 3.3: This Butterfly diagram illustrates the way in which technological and biological nutrient-based products and materials circle through the system (Ellen McArthur Foundation, 2019).

Cradle-to-Cradle (C2C)

In their book Cradle to Cradle: Remaking the way we make things, McDonough and Braungart (2002) introduce the concept of Cradle to Cradle (C2C). According to the theory of Cradle-to-cradle, the current way of producing is toxic and consists of one-way material flows, also known as "cradle to grave". A Cradle to Cradle system is powered by renewable energy and in this system, materials flow in safe, regenerative, closed-loop cycles. "Simply put, C2C designs industrial systems to be commercially productive, socially beneficial, and ecologically intelligent" (McDonough et al., 2003).

McDonough et al. (2003) have also identified three tenets of cradle-to-cradle design; waste equals food, use current solar income, and celebrate diversity.

Waste equals food beholds that waste does not exist in nature since all organism's processes contribute to the health of the whole ecosystem. When these regenerative systems are recognised by engineers and designers, McDonough et al. (2003) state that all material can be designed as nutrients that flow through natural or designed metabolisms. A way is to design products as biological nutrients by for example producing the textiles and packaging from natural fibres so they can biodegrade safely and restore the depleted soil nutrients. Technological products such as carpet yarns which are made from synthetics could be repeatedly depolymerised and repolymerised so they are providing high-quality and hi-tech ingredients for generation after generation.

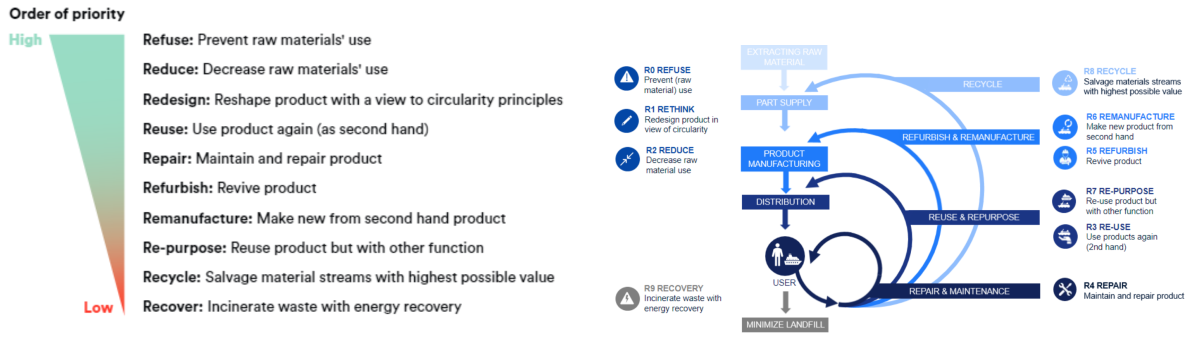
Using current solar income stands for using directly collecting solar energy or tapping into a passive solar process where natural light can be piped into an indoor space. But also for example wind power can be captured. It stands for making sure that both energy and material inputs are renewable rather than depleting.

Celebrate diversity states that natural systems thrive on diversity. In a healthy ecosystem, every living thing has developed a unique response to its surroundings and works together with other organisms to sustain the system.

The C2C vision sets a course for what designers and users need to strive for and The 12 Principles of Green Engineering can be used to find a way how to do it. This is done by stating what a designer should strive for and what a design should focus on. Examples are designing with a focus on maximising mass, energy, space, and time efficiency, or design with a focus on renewable energy and material inputs. The 12 Principles are added in Figure A.1.

10R

The 10R ladder shows the ambition level of circular strategies. The goal of the ladder is to increase awareness of the fact that the circular economy is not only about recycling waste streams and that strategies higher on the ladder usually have a lower impact on the environment. As can be seen in Figure 3.4, Refuse of use should have the highest priority, after which reduction becomes the most important strategy. Figure 3.4a shows the 10R theory as visualised by Cramer (2020), whilst Figure 3.4b depicts the 10R theory as visualised by Damen, a combination between the butterfly diagram as already shown in Figure 3.3 and the visual of Cramer. The fact that circularity is a concept of which everybody has their own interpretation can also be seen here since the reduce and rethink/redesign R's are switched around in the two approaches. For the lowest R, any remaining waste which cannot be recycled should be incinerated with energy recovery, but this can not be seen as part of a circular economy (Cramer, 2020).



(a) The 10R's as visualised by Cramer (2020)

(b) 10R as visualised by Damen

Figure 3.4: The 10R's

To transform from linear into circular products, often technical innovation is considered important, but the product chain will also need to be completely reorganised. This is because the raw materials and components should be suitable for reuse and recycling. Additionally, to ensure a good product, the production process might need adjustments to include the new design requirements. To enable circularity, it is very important that after use, a collection, take-back and/or reuse system is available so the product can enjoy a second life. In case it is not possible to reuse the product, the resources should be recovered with the highest potential value and returned to a producer to make new products. To achieve this goal, all stakeholders must make a contribution to the process. The government could for example set the necessary preconditions but can also remove economic and legal obstacles, facilitate circular initiatives through innovation funds and promote circular products by being a launching customer (Cramer, 2020).

Reike et al. (2018) suggest to discriminate two related life cycles, a product *Produce and Use* Life Cycle and a Product *Concept and Design* Life Cycle in connection with the 10R's. They reviewed 69 academic R-imperatives on their conceptualisation. noted the use of 38 different words starting with 're-' in varying combinations, with a ranging number of R-imperatives from 3Rs to 10Rs. In these theories, 60% of the authors applied a clear hierarchy with definitions of the terms used but in 40% no clear hierarchy and the meaning of the concepts used remained suggestive or vague.

ReSOLVE

The McKinsey Center for Business and Environment (2016) also developed a framework regarding what circular economy entails: ReSOLVE. ReSOLVE takes to core principles of circularity and relates them to six actions": Regenerate, Share, Optimise, Loop, Virtualise and Exchange. Regenerate stands for shifting to renewable energy and materials, regenerating the health of ecosystems, and returning recovered biological resources to the biosphere. The goal of the action "Share" is to maximise the utilisation of products by sharing privately owned products or public sharing of pools of products, but also prolonging the life span of products by maintenance, repair and design for durability. Optimise states to improve the performance and efficiency of products, but also remove waste from the supply chain of the product. Additional big data, automation and remote sensing should be leveraged. The Loop action desires to keep materials and components in closed loops and prioritise the inner one where a difference is made between finite materials and renewable materials. Finite materials should be re-manufactured and (as a last resort) recycled. Anaerobic digestion and the extraction of biochemicals need to be involved for renewable materials. Virtualise stands for delivering utility virtually. Lastly, Exchange has the goal to replace old materials with advanced, renewable ones and apply new technologies. For multiple economic activities, the profit potential has been mapped by McKinsey Center for Business and Environment (2016). For example, Construction has a high profit potential by use of the actions Share and Loop, whilst Education has a high profit potential for the action Virtualise. (McKinsey Center for Business and Environment, 2016)

3.1.2. Conclusion of the definition of circularity

Even though the frameworks differ in name and exact definition, there are many overlapping principles. First of all the main takeaway for every circular framework is to have as little waste as possible and ideally never throw any materials away by closing the loop. But also the way materials are kept in the loop shows some overlapping principles within the frameworks; words such as reuse, refurbish, recycle etc are in the butterfly diagram of the Ellen McArthur Foundation (2019) but also in the 10R framework. The environmental impact besides material circularity is not part of these frameworks. This was also defined in the scope, to not look at other environmental impacts but purely circularity in terms of material reuse and using as little material as possible. To continue this project, the 10R framework as visualised by Cramer (2020) will be chosen to work with. This is because it shows clear steps for the circularity level of a product/material in every stage of the life cycle of a product; from design until the end of life (in its current function). Additionally, even though R1 until R8 can all be seen as circular, it is important to make a clear distinction between the levels of circularity, something that other frameworks have a less clear definition of. Another but less important reason to choose this framework is that Damen already uses this framework. The 10R framework will be explained and elaborated upon more extensively in subsection 4.4.2. This framework does not have a clear way of measuring on which step of the circularity ladder a system is currently functioning, but to measure how circular products are, again multiple frameworks and methods exist. These will be elaborated upon in the next section.

3.2. Measuring Circularity

In this section the second sub-question will be answered; *How can circularity be measured?*. When measuring circularity, four levels of measurement could be considered. The Regional level, also referred to as the macro level, is the circularity assessment level that focuses on geographical areas. One level below this, the meso level, is the inter-organisational level that focuses on groups of organisations. At the micro level, there is the organisational level that focuses on an individual organisation. Lastly, the most detailed level is the nano level, which is at the product/service level. At the nano level, the focus is on a single product (Balder, 2021). This research will focus on circularity at this product/service level. To measure circularity, once again many different methods and tools are available, therefore only the most commonly used and known methods are considered and explained in this section. Since the focus is on the nano level, measurement methods that focus on the other levels, such as the commonly known Circulytics tool developed by the Ellen MacArthur Foundation (2020) will be excluded from this research since it focuses on the micro level. Tools that focus on the micro level mostly focus on an organisation as a whole whilst the focus for this research is on the product level focusing on one product at a time.

3.2.1. Overview of methods

Just like the definition of circularity, there are many frameworks available for measuring circularity. In this sub-section, six methods will be set out.

CEI

To measure the environmental impact of any product during its life cycle, the Life Cycle Assessment (LCA) method is commonly used. Although it provides good insights about the environmental burden of each product and/or industry it is not always cost-effective because a detailed LCA requires large amounts of data and therefore it is time-consuming. Moreover, the LCA provides only information on the environmental domain of sustainability, whilst neglecting the economic and social domains which should be addressed simultaneously (Di Maio and Rem, 2015). This is one of the driving forces for developing a new approach by Di Maio and Rem (2015); The Circular Economy Index (CEI). The CEI aims to introduce the economic value of the materials embedded in consumers' products as the property to be measured and accounted for. One of the important aspects is that the CEI needs data from the companies' financial reports and the Bureau of Statistics so that the analysis of the performance is possible at the firm as well as sector level. The CEI intuitively represents the effectiveness of recycling firms at extracting value from the processed materials and therefore it represents a decision-making tool which will help managers and policymakers to steer decisions towards value creation and technological innovation.

The CEI proposed by Di Maio and Rem (2015) is the ratio of the material value produced by the recycler (market value) to the material value entering the recycling facility. Mathematically given as:

$$CEI = \frac{\text{Material value recycled from EOL product(s)}}{\text{Material value needed for (re-)producing EOL product(s)}} \tag{3.1}$$

where EOL stands for End Of Life. The CEI solves some problems of LCA and mass recycling rates since, unlike mass recycling rates, the CEI adjusts itself automatically if some specific material becomes more expensive because it is less available, e.g. as a consequence of strategic issues, or if the material becomes cheaper because of a very efficient recycling technology (Di Maio and Rem, 2015).

The developers of the CEI state that whilst it would not be possible to enforce a law requiring that all companies should perform an LCA, it will be possible to do it with the CEI because it is easy to interpret and compute and does not require extra human resources to be done (Di Maio and Rem, 2015). A policy can only be successful if there is a drive (the index), if you can measure it, if it is clear to everybody what it means, and if it is related to what we want to achieve.

The advantage of the CEI proposed here is that it provides a clear indication of how good a recycling company is in valorising the materials it processes and in combination with the Key Recycling Info gives environmental, technical and economic information which is useful to better perform life cycle analysis, material flow accounting analysis, and input-output analysis, to design recycling processes and to predict the amount of stock-in-use materials (Di Maio and Rem, 2015).

3DR

O'Grady et al. (2021) propose a circular design index for the built environment focused on **d**esign for **d**isassembly, **d**econstruction and **r**esilience (3DR). Design is considered the most important stage to be able to comply with a circular economy. Disassembly focuses on the separation of materials and can happen at any stage in the life cycle of a building, during renovations, or at the end of the building's life. Deconstruction is the removal of a building's structural elements and the relocation of part of or the whole building. Resilience is the reduction of the ongoing consequences of a disruptive event, such as dismantling or relocating a structure.

"The 3DR method is developed to calculate the circular economy index of a building based on considerations made during the design stage, including disassembly, deconstruction and resilience of the buildings' structural fabric, finishes and components. These considerations are influenced by the potential second life of materials, including reuse, recycling, downcycling or disposal, the difficulty of separating materials from each other and the tools needed to complete the process" (O'Grady et al., 2021).

To use the method, O'Grady et al. (2021) have developed four steps. First, an analysis of connections and components that can be disconnected from the building needs to be performed. Secondly, the scope needs to be defined to clarify whether the building needs to be disassembled and whether its components will be reused, recycled or be put into a landfill. Thirdly, The Disassembly Index (DI), the Deconstruction Index (DE) and Resilience (R) need to be calculated after which the 3DR index can be calculated. Lastly, the results will be interpreted and the building will be improved.

$$
\begin{aligned}
DI &= \sum_{i=1}^{n} \left(DIt_i \times \ DIm_i \times w_i\right)/w_T \\
DE &= \sum_{j=1}^{m} \left(DEt_j \times \ DEm_j \times w_j\right)/w_T \\
R &= \sum_{k=1}^{t} \left(Re_k \times w_k\right)/w_T \\
3DR &= DI \times a + DE \times b + R \times c
\end{aligned}
\tag{3.2}
$$

a, b, and c are index influencers which need to be modified for each scenario (such as end-of-life or repurposing). The sum of a, b and c together must always be equal to 1. ”A higher 3DR value (closer to 1) indicates that the building has a high degree of disassemblability and deconstructability and is built with resilient components that may be disassembled multiple times. A lower 3DR value (closer to 0) indicates that the building has not been designed following circular economy principles. A 3DR value equal to 0 means that the structure is fully linear: it cannot be disassembled, reused or recycled” (O’Grady et al., 2021).

Material Circularity Indicator (MCI)

The Material Circularity Indicator (MCI) was developed by the Ellen MacArthur Foundation in cooperation with ANSYS Granta to identify indicators that assess how well a product performs in the context of a circular economy. Material flows and a range of complementary indicators are encompassed, so companies can estimate how advanced they are in the process of shifting from linear to circular in terms of their products and materials. The indices can measure how restorative and regenerative the material flows are by use of a main indicator; The Material Circularity Indicator. Additional impacts and risks are taken into account by complementary indicators. The indicator differentiates between the biological cycle and the technical cycle, focusing on the restoration of material flows at product and company levels. The MCI differs from Life Cycle Assessments (LCA) in two ways. ”1) LCA focuses on deriving the environmental impacts throughout the life cycle of a product for different scenarios, whereas the MCI concentrates on the flow of materials throughout the use of a product. 2) Many of the input data required for an LCA are the same as for the MCI and the complementary impact indicators may indeed be derived from an LCA approach (e.g. relevant standards to assess the Carbon footprint of a product). Additionally, in the future, the MCI could be one of the parameters considered as an output from an LCA or eco-design approach alongside those already typically used” (Goddin et al., 2019).

The indicator can be used for a product to measure to which extent linear flow was minimised and restorative flow was maximised. For the inflow, a distinction is made between virgin feedstock; raw materials that were not used before, reused components, and recycled feedstock. For the outflow again a distinction is made between materials that are collected for recycling, materials going to energy recovery and components that are collected for reuse.

Eco-indicator99

The Eco-indicator99 expresses the total environmental load of a product’s or process’ life cycle in a number (Baayen, 2000). Both Cozijnsen (2019) and Ettema (2021) used this approach to measure the impact of yachts on the environment during their lifetime. This is a tool to perform an LCA of a product or process. As explained before, an LCA differs from a measurement of circularity. Since this research focuses on circularity, which is not the same as environmental impact, this method will not be considered further.

Circular Transition Indicator (CTI)

Damen Shipyards uses a tool developed by WBSCD to measure circularity; the Circular Transition Indicator (CTI). The goal of the CTI is to provide insight into circularity on a company level to drive the transition towards a circular economy by encouraging businesses to adopt innovative business models that improve company longevity and resilience. It measures circularity by looking at the inflow and outflow of materials used. The method is not open access and is presented on a website where all information can be filled in and the tool automatically calculates the circularity level. Both the in and outflow can be subdivided into linear and circular flows. Circular inflow covers materials that have been used before and/or that are from a renewable source, and circular outflow takes into account products that can be used again. The linear inflow is non-renewable products and/or products that originate from a virgin resource (so they have not been used yet). The linear outflow is about non-recoverable products and waste streams. The inflow and outflow are measured in percentage of mass. The combined percentage of circular inflow and circular outflow gives the total material circularity of a product. There is a difference made between the recovery potential of a material, and the actual amount of material recovered (wbcsd, n.d.-a). Similar to the MCI method, the type of recovery can be divided into reuse, repair, refurbishment, remanufacturing and recycling.

Circular Product Readiness Method

Boorsma et al. (2022) conclude that the existing indicator methods have multiple flaws; ”they lack depth with regards to a circular design, are incomplete, or do not use design semantics” (p.1). Therefore they set up five criteria and combined five existing methods (C-Indicators Advisor, Circulytics, MATChE, CE Indicator and CE transition in product chains (CE-TPC) to come up with a new framework, named the Circular Product Readiness Method. The final set of themes and indicators is shown in Figure 3.5. The goal of the method is to track the implementation of circular design and gain insight into performance and improvement opportunities.

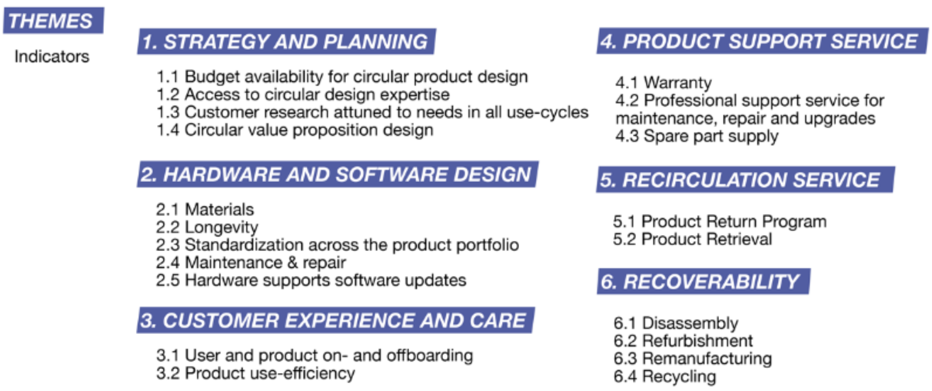


Figure 3.5: The final set of themes and indicators (Boorsma et al., 2022)

In order to see the level of circularity for each indicator, a scoring system with questions is set up where points can be scored per question. The questions include assessing the circularity level on a company level but also material level is addressed. The importance of the themes and indicators depends highly on the type of product that’s being assessed. As an example, an ASKO washing machine is assessed in the paper, where the outcome is circular product readiness level as a percentage.

3.2.2. Conclusion on methods for measuring circularity

There are many ways of measuring circularity which all have pros and cons. An overview of the required information that is needed to use each calculation method is given in Table 3.1. For the CEI tool, not a lot of information on the lifetime of the products is needed, since it expresses the (economic) effectiveness of recycling firms, focusing only on the recycling part, whilst MCI, CTI and 3DR also focus on the inflow of materials and the lifetime of the product before the recycling phase. The 3DR method however is very flexible and indexes can be changed to get the desired outcome. Another downside of the 3DR framework is that it was developed for the construction industry. Even though the steps of constructing a building are relatively similar to shipbuilding, it is not exactly the same since a ship is constructed, used and demolished at different locations, making it harder to control the circularity steps. For the

MCI and CTI methods, a clear distinction is made between the different levels of circularity of the 10R framework. However, to fill in the inflow and outflow of materials, this information needs to be known. This means that for example for assessing a vessel, good communication with suppliers is required. The MCI method is more extensive than the CTI tool, addressing the biological cycle and even utility and recovery efficiencies can be taken into account. A downside of the CTI tool is that is an actual tool which needs to be acquired by a company of individuals to use it, whilst the MCI formulas are publicly available. What comes clear from the CTI and MCI methods, which in a less explicit way was also already addressed in the presented frameworks of the definition of circularity, is that inflow is as important as outflow. The total circularity is the average of the inflow of circular materials and the outflow of circular materials. Regarding the Circular Product Readiness method, it does not only asses circularity on the product level but also takes into account a company's circularity strategy. Also, the questions to assess the level of circularity are very broad, the answers are hard to measure and can be filled in looking from different perspectives so the user can tweak the results as he/she likes. However, it is a method that takes the time a product is used (slightly) into account. This can be an important factor since the longer a material can be used for the same product, the less often the loop needs to be walked through and closed. Finally, as said before, the Eco-Indicato99 does not asses circularity enough but performs an LCA on environmental impact.

To continue this research, the MCI method will be chosen. This is because it makes a clear distinction between the different circularity levels of the 10R method, the formulas are clear and open access, and the focus is on the product level. The MCI method will now be explained in depth.

Table 3.1: Overview of the required input per circularity measurement method

CEI	3DR	MCI
Material value of recycled products	Availability, dimensions, and types of tools required to disassemble components (DIt) or deconstruct a building (DEt)	% of mass of recycled, refurbished and reused parts/components in the inflow
Material value needed for (re)producing products	People or equipment required to move components to another building (DIm) or move components following deconstruction (DEm)	Lifetime of the product and the average lifetime of an industry-average product of a similar type.
	The resilience of components	The number of functional units achieved during the use of the product and the average number of functional units achieved during the use of an industry-average product of a similar type
	Total weight of building and seperately the weight of all components	% of mass of outflow into refurbishment, remanufacturing, recycling, repurposing, reuse and recovery/landfill
Eco-indicator99	**CTI**	**CPRM**
All materials and processes used to create a product	% of mass of recycled parts/components in the inflow	Information about company budget on circularity, research into circularity, design of circularity, flow back loops, etc.
The Eco-indicator tool to determine values that are linked to the materials and processes.	% of mass that can be recycled in the outflow	Fraction of previously used materials, amout of biodegradable materials, used design strategies, packaging
	The percentage of mass that is actually recycled	Information on the manual, compatibility, safety risk, customer experience, etc.

3.3. The Material Circularity Indicator

The chosen measurement method is the Material Circularity Indicator (MCI). As explained before, this method distinguishes between the inflow and outflow of materials in a system. A full explanation of the method will be given in this section. First, the MCI method as presented by the Ellen McArthur Foundation and Ansys Granta Edupack will be explained after which adjustments to the method will be proposed.

3.3.1. Overview of the method

The MCI can be used for the analysis of material flows for technical materials. A visual overview of the method is shown in Figure 3.6. For the inflow of the product, a distinction is made between virgin feedstock and non-virgin feedstock, after which the non-virgin feedstock is divided into recycled and reused materials. Then there is the product lifetime and after being used by the product owner, the end of life can be divided into recycling, reuse and disposal in the form of landfill or energy recovery. Any product that contains only virgin feedstock and ends up in a landfill at the end of its lifetime is seen as a fully linear product. Contrary to a fully circular product, which contains no virgin feedstock and is completely collected for recycling or component reuse. All inputs and outputs are measured in terms of mass. These material flows are only focused on the materials that end up in the final product, whilst there are also many other materials flows such as waste streams that occur during manufacturing or packaging. These flows will not be considered because in that case, the whole production and transport process of the product will also have to be examined, which is out of the scope of this research.

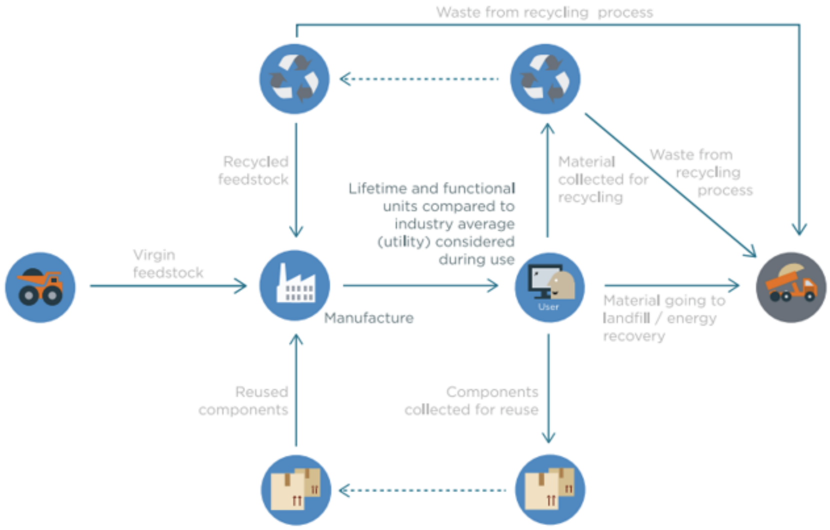


Figure 3.6: Diagrammatic representation of material flows (Goddin et al., 2019)

Input of materials

The inflow of the material can be divided into recycled, reused, and virgin materials. The M stands for the total mass of the final product. F_R is the fraction of feedstock coming from recycled sources and F_U represents the fraction from reused sources. So the mass of the virgin material (V) used can be calculated by Equation 3.3.

$$V = M(1 - F_R - F_U) \tag{3.3}$$

To get information about the fraction of reused and recycled materials in existing systems, good communication with suppliers is extremely important because they have this information. When designing a new product, implementing as many reused materials and after that as much recycled material is very important in order to reach an as high as possible circularity level. It is important to note here that production losses such as plate cutting or transport losses where packaging was involved are not considered here but only the final product is assessed. A very big downside of using mass as the measuring quantity is the fact that the hulls of ships are often built out of steel, having a very large weight and thus a very big influence on the circularity calculation. To make sure the influence of the steel hull is not a big factor in the circularity assessment, it might be best to assess systems on board separately instead of assessing the ship as a whole. Next to that, rare or hazardous materials might not weigh that much but will have a big influence on the whole vessel and are now not taken into account that much.

Between manufacturing and end-of-life, there is the lifetime of the product where the user has control over the system. The user decides what happens with the product in case it becomes obsolete. Will it be repaired in case of damage? Will it be sold for reuse in case it is not needed anymore? Will it be sent for remanufacturing in case of a breakdown? These are all very important decisions during the product's lifetime. Unfortunately, the R-values of Reuse, Repair, Refurbish and Remanufacture are not taken up in the MCI tool explicitly. However, when a product is reused instead of recycled, the inflow of virgin materials will differ, so a difference can be seen there. Remanufacture is taken up in the part where components are collected for reuse and recycling and recovery are also stated in the MCI tool.

Output of materials

For the outflow, just like the inflow, the materials will be divided into recycled materials, components collected for reuse and materials that will be going into landfill or energy recovery. C_R is the fraction of mass being collected for recycling at the end of the use phase, and C_U is the fraction of the mass going into component reuse. To calculate the amount of waste that will be going to landfill or energy recovery, Equation 3.4 can be used. However, energy recovery is only part of the circular strategy if it regards a biological cycle, so in the case of a vessel, which only has technical cycle systems, it will not be seen as a circular strategy. This however shows that the use of biological materials can increase the circularity of a product, since in that case energy recovery can be seen as a circular option.

$$W_O = M(1 - C_R - C_U) \tag{3.4}$$

In the input of waste, there is also the possibility to include the waste generated during recycling processes, W_C and W_F. Since the process of recycling is out of the scope of this research, it will be assumed that there will not be any waste during the recycling process so this will be excluded from the calculation. Therefore the waste, W, will be equal to W_O.

To get information about the direction of the outflow of materials, certain key indicators are required. These indicators can also be referred to as system properties and will be explained in section 5.1.

Calculation of the circularity

The material flow is divided into linear material flow and circular material flow. The Linear Flow Index (LFI) measures the part of material flowing in a linear way, so sourced from virgin materials and ending up as landfill or energy recovery. The LFI can be calculated by dividing the amount of linear flow material by the sum of the total material flow as shown in Equation 3.5.

$$LFI = \frac{V + W}{2M} \tag{3.5}$$

The MCI offers the possibility to include utility, so the combination of lifetime and intensity of use, into the calculation for the final material circularity. The method calculates utility by creating a ratio for the lifetime and intensity of use compared to industry averages. For a lifetime the component L/L_{av} is used, accounting for reductions in the waste stream in a given amount of time for products that have a longer lifetime (L) than the industry average (L_{av}). This longer lifetime can for example be due to the R-values for reuse, repair, refurbish or remanufacture. This means that in case the lifespan of a product is doubled, the amount of waste generated and the virgin materials consumed annually in the linear stage of the product's life cycle are reduced by half. The same goes for the case in which the lifetime of a product is halved, then the (linear) waste created and virgin materials used annually are doubled.

The intensity of use is represented by U/U_{av}, reflecting the extent to which a product is used to its full capacity. U is (on average) the number of functional units achieved during the use of a product, where a functional unit is a measure of the product's use. Examples are a kilometre driven by a car or one wash cycle for a washing machine. U_{av} is (on average) the number of functional units achieved during the use of an industry-average product of a similar type.

These two components can be used to calculate the utility (X), as shown in Equation 3.6.

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right) \tag{3.6}$$

So the higher the lifetime and use frequency, compared to the industry average, the higher the utility of a product will be. As said before, this value can be increased by the R-values of reuse, repair, refurbish or remanufacture. The overview of all the material streams used in a system at the being, during and at the end of its lifetime is shown in Figure 3.7.

Now, to calculate the Material Circularity Indicator, the LFI and a factor $F(X)$ are used. $F(x)$ is a function of the utility X given by $F(x) = \frac{0.9}{X}$. F is designed to penalise products with short lifetimes and poor utilisation, and vice versa. F is also chosen in such a way that improvements in the utility of a product have the same impact on the MCI as the reuse of components leading to the same amount of reduction of virgin material use and unrecoverable waste in a given period of time.

To calculate the MCI, the F is multiplied with the LFI and subtracted from 1, resulting in Equation 3.7. Since for mainly linear flowing products where the LFI is almost one the MCI could in that case be negative, the MCI is limited to a minimum of 0.

$$MCI = 1 - LFI \cdot F(x) \tag{3.7}$$

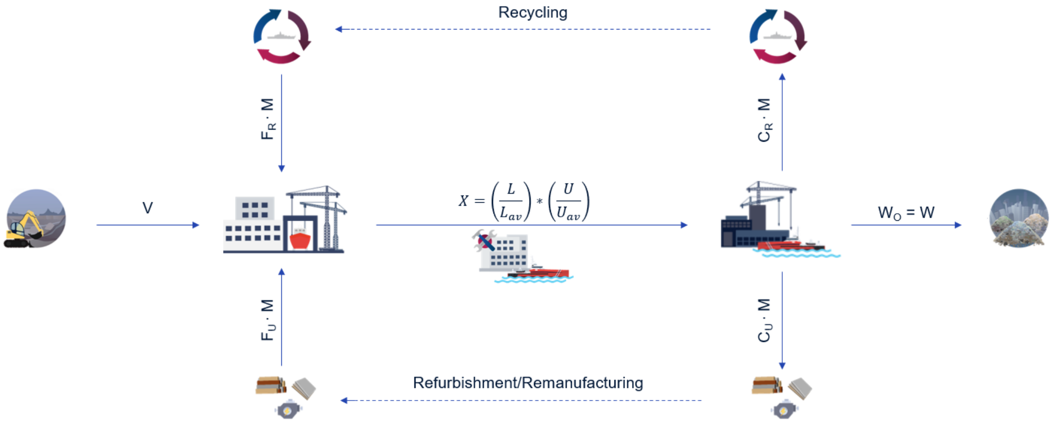


Figure 3.7: Overview of the material streams for calculation of the MCI

3.3.2. Proposed adjustments to the MCI method

The waste from recycling processes that were present in the original MCI method is left out. Next, extra changes to the material flows present in the MCI method will be proposed in this section. This is because the material flows in the original method only show flows for a life cycle of the same product. However, when looking at, for example, the circularity indicator of repurposing, the circularity loop does not have to be limited to a single product. The same goes for recycling; often recycled parts are used in other products than the original products. Think about the carpet on the new "Waterbus" designed by Damen Shipyards which is made from recycled fishing nets. This is a circular material from a different product. A distinction will be made between reused parts and reused components. Reused components are bigger and can be seen as refurbishments. Parts that are reused can be seen are remanufacturing. This only goes for components and parts that are used in the same application. In case of use in another industry, the flow will be seen as repurposing. Therefore, a new visualisation of the material flows is shown in Figure 3.8

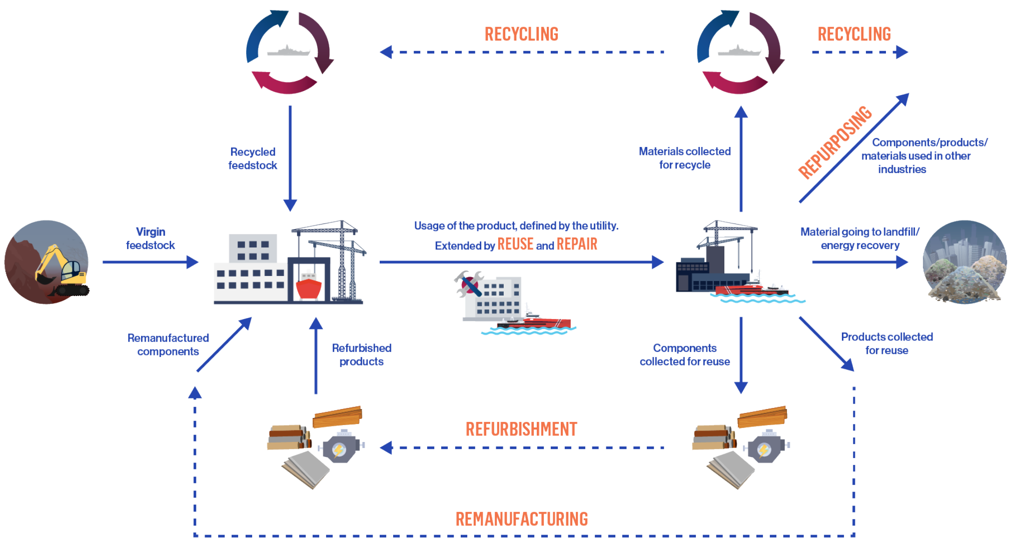


Figure 3.8: Visual of the material flows when combining the 10R framework with the MCI tool

This also means that the calculation of the MCI needs to be adjusted and extra symbols are required. For the refurbishment flow, F_F and C_F will be used. For the remanufacuturing flow, F_M and C_M are introduced. Lastly, for the repurposing stream, C_P is used as a symbol. This means that the calculation of the inflow of virgin materials will be and outflow of waste will come down to:

$$V = M(1 - F_R - F_M - F_F)$$
$$W = M(1 - C_R - C_M - C_F - C_P) \tag{3.8}$$

The rest of the calculations for the MCI will remain the same. The new overview of symbols and calculations is shown in Figure 3.9.

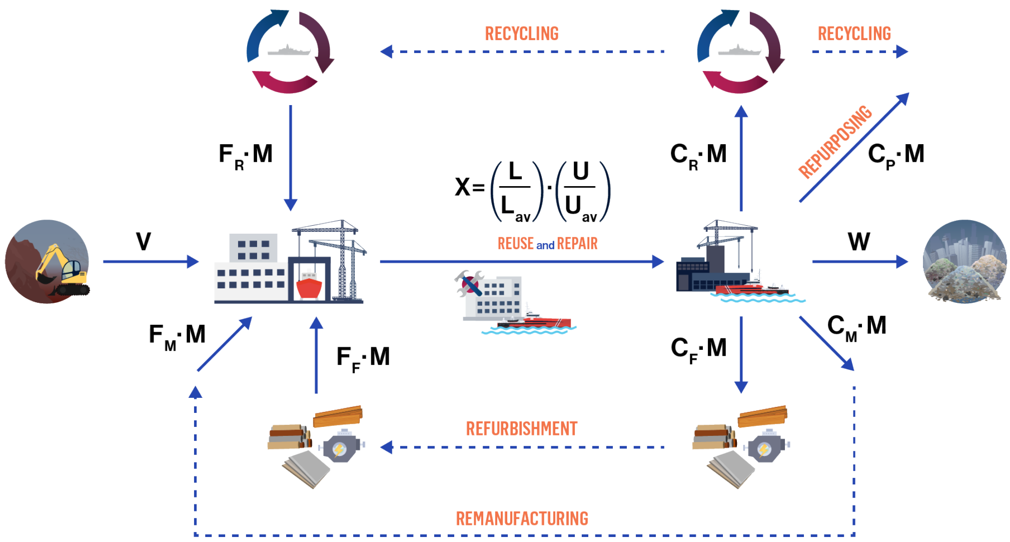


Figure 3.9: Visual of the material flows when combining the 10R framework with the MCI tool in symbols

4

Design approaches

In this chapter, the third research question will be answered; *What is the best design approach to address circularity in ship design?*. To do this, ship design approaches will be elaborated upon. After this, the current design approaches for circularity used for consumer goods will be set out. The focus will be on consumer goods since circular design approaches are already applied there. The design approaches for circularity are on a more detailed level than the ship design approaches because circularity requires a more detailed approach than ordinary design approaches. Finally, the difference between normal consumer good design and ship design will be explained to show the need for an approach which includes circularity but is applicable to ship design.

4.1. Design approaches in shipbuilding

In this section the first sub-question will be answered; *What are the design approaches for shipbuilding?* When it comes to shipbuilding, four classes of high-level design approaches are often distinguished; Point-based design, Set-based design, Optimisation-based models, and System-based methods (Erikstad and Lagemann, 2022). Each of the four methods will be elaborated upon and a decision will be made for the use of one of the approaches. Finally, the current design approach within Damen Shipyards will be elaborated upon and a conclusion will be drawn on how to include circularity in the design for shipbuilding.

4.1.1. Point-based design

The most illustrated form of point-based design is the design spiral model. Evans (1959) was the first one to present the design spiral model. He made a model of a rational overall design procedure as applied to a "typical surface cargo ship problem" (Hopman, 2021). By many designers, this model is considered to be the "classical" design approach but it is also the one most commonly used in industry (Erikstad, 2022). The focus of the model is on how to estimate or calculate and balance ship design parameter values in a time-effective way using an iterative process. The starting point of the spiral is, in practice, a previous design project with similar capabilities and requirements. The method manages the design problem by first proposing a form, after which insight is derived by analysing the functional performance to achieve feasibility or improvement. The method could be summarised as Propose-Analyse-Evaluate-Decide. Two main drawbacks of the strategy are the inefficiency in exploring the design space and the risk of being tied too closely to the single starting point of the iterations, making it hard

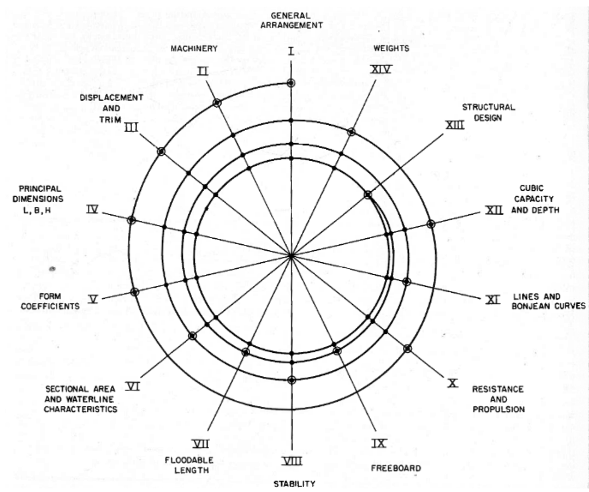


Figure 4.1: Evan's design spiral (Evans, 1959)

to implement innovations in the design (Hopman, 2021).

4.1.2. Set-based design

The simplest form of set-based design is generating a number of design points, either systematically or randomly, and analysing the performance of each of the points after which the best feasible design among these is selected (Singer et al., 2009). Another more intelligent approach would be to first perform broad and shallow research through the design space, then a more narrow and deep investigation into the most promising regions. This design method can be used to overcome the single starting point problem by concurrently handling multiple design solutions (Erikstad, 2022).

4.1.3. Optimisation-based design

According to Erikstad (2022), the optimisation-based design aims to capture the complete design in a well-structured model that contains objective function and constraints. Optimisation algorithms can be used to find a feasible and optimal solution. However, real-world design problems are often too complex to fit into the strict mathematical requirements of a classical optimisation approach. To overcome this, heuristics and nature-inspired methods such as genetic algorithms, particle swarm optimisation, etc. can be applied. In these models, the requirements for a well-behaved, continuous, and differential design space are less strict.

4.1.4. Systems-based design

Kossiakoff et al. (2011) states that ”The function of systems engineering is to guide the engineering of complex systems”. Where a system is seen as ”a set of interrelated components working together toward some common objective” (Kossiakoff et al., 2011). System engineering differs from other engineering disciplines such as mechanical and electrical engineering in three ways:

1. It is concerned with both external factors and the engineering design of the system and focuses on the system as a whole. This means that it emphasises its total operation.
2. System engineers are responsible for reflecting the needs of the user and creating a functional design. So even though the primary purpose of systems engineering is to guide, systems engineers play a key role in system design.
3. Due to the complexity and diversity of elements in a system, different engineering disciplines are required to be involved in the design and development. Each system element must function well in combination with the other system elements. So all elements must be engineered in such a way that it is ”assured that the interactions and interfaces between system elements are compatible and mutually supporting” (Kossiakoff et al., 2011).

In systems engineering, a system can be broken down into systems, sub-systems, components, sub-components, and parts (Hopman, 2021). A visual of the different levels in systems engineering is shown in Figure 4.2. A system is performing a significant, useful service and could be part of a (usually external) super system. A sub-system operates a subset of the overall system functions. If there is a system of systems, the sub-systems must be able to operate independently. The components perform a primary function which is often physical, a building block representing things (so not processes). The sub-components perform elementary functions, composed of parts. Lastly, the parts represent elements with no significant function.

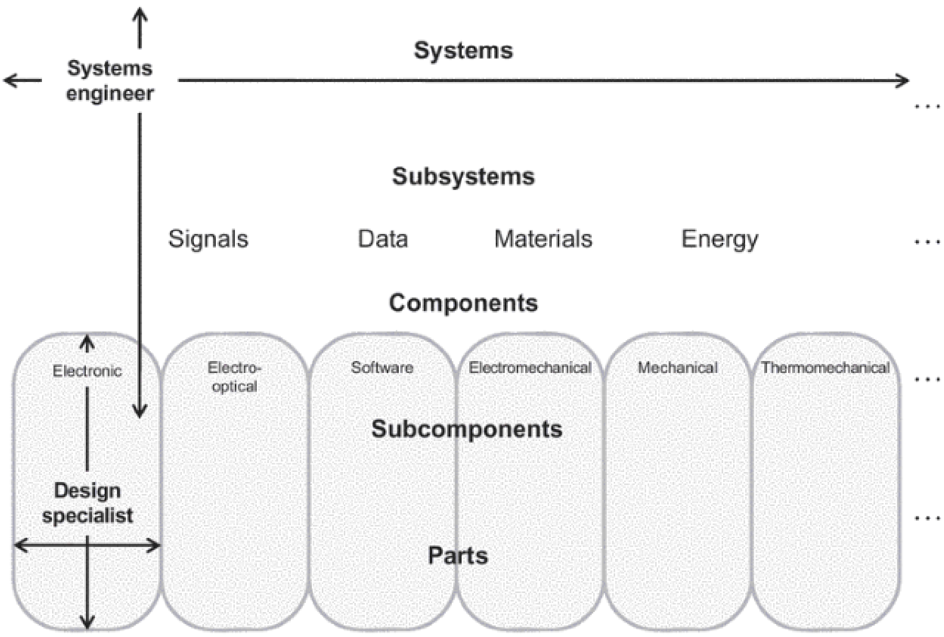


Figure 4.2: Knowledge domains of the systems engineer and design specialist (Kossiakoff et al., 2011)

4.1.5. Conclusion on ship design approaches

An overview of the four presented design approaches is shown in Table 4.1. Of the four, systems engineering is the preferred method because it defines the customer needs and required functionality early in the development cycle, focuses on documenting requirements and after that proceeds with design synthesis and system validation while considering the complete problem. Next to that, the method considers both business and technical needs of all customers in order to provide a quality product that meets the user's needs. This solves some of the problems for the other methods such as the point-based design where the design spiral is often used and the starting point is so important that it is hard to implement innovations. As mentioned before, none of the four design approaches takes circularity into account. This might also be because circularity is hard to express in terms of an optimisation code or functional requirement. Therefore there is a need to explore design approaches for a circular product. Because circular design is already quite common for consumer goods, these approaches will now be elaborated upon.

Table 4.1: Overview of the design approaches for ship design

	Advantages	**Disadvantages**
Point-based	- Iterative process to estimate or calculate ship parameters in a time-effective way	- Inefficient in exploring the design space - Risk of being tied too closely to the starting point - Hard to implement innovations in design
Set-based	- Broad set of parameters with gradual narrowing towards an optimal solution	- Many parameters are open until late in the design process - Tade-offs need to be made in this strategy, meaning options should be comparable.
Optimisation-based	- The best possible solution can be found	- Design needs to be framed as an optimisation problem - Accurate and efficient capture of typical ship design problems is too complex
System-based	- Defines customer needs and required functionality early in the development cycle - Considering the whole problem whilst also focusing on documenting - Both business and technical needs are considered	- Great level of detail is required to consider all systems

4.2. Systems Engineering

Since systems engineering was chosen as the ship design approach to include circularity into, this approach will now be further elaborated upon. Engineering uses known principles to create practical outcomes. However, innovation produces new materials, devices, and processes. Sometimes the characteristics of the innovations are not fully known due to a lack of measurements or understanding. In that case there is a risk in producing an inferior system where the application of the latest technology to the system development has failed meaning this system could become prematurely obsolete. The approach to the early application of new technology in systems engineering is covered by 'risk management'. Achieving the best balance of risks, so deciding on which system elements are to take advantage of technology and which will be based on proven concepts, is one of the essential tasks of systems engineering. Another particular concern of system engineering is the human-machine interface and other people-system interactions, driven by the increase in automation.

When designing a system, different kinds of trade-offs need to be made in different engineering phases. For example, during the contracting phase, each contractor will try to design the most cost-effective option, commercial producers will always try to develop a new market of increased market share, and there is almost always competition between the characteristics of a system. With the characteristics of a system, the speed and range of a car can be a good example; the two are dependent on each other. The different forms of competition asked to engineer and produce the best performing, most affordable system in the least possible time, exerting pressure on the system development process. This so-called "trade-off analysis" is one of the practices of systems engineering. There are several steps in systems engineering:

1. Needs analysis
2. Concept exploration
3. Concept definition
4. Advanced development
5. Engineering design
6. Integration and evaluation
7. Production
8. Operations and support

Next to these eight steps, there are two additional steps that occur many times in the system engineering process: Decision analysis and support, and software systems engineering. Decision analysis and support is a process that contains several steps and the formality of each step is dependent on the type and complexity of the decision. Software systems engineering is the application of principles to the software engineering discipline, where software engineering is "the development and delivery of software products, stand-alone or embedded" (Kossiakoff et al., 2011).

Within systems engineering, an application of the theory is the Requirement-Functional-Logical-Physical model (RFLP). The complexity of systems is not only due to a large amount of connected physical components, but also the functional interdependencies play a huge role (Li et al., 2020). By working together, various systems can achieve one function. This so-called functional integration is associated with the different power sources and information flow between the systems. The RFLP model can be visualised in a V model which shows the "top-down" decomposition of requirements and the system's specifications, and the "bottom-up" where the integration of parts and their validation is shown. The requirements need to be validated against the higher level of requirements and user needs, therefore there are horizontal validation rules. A visualisation of the RFLP model in the V-shape created by Damen Shipyards is shown in Figure 4.3.

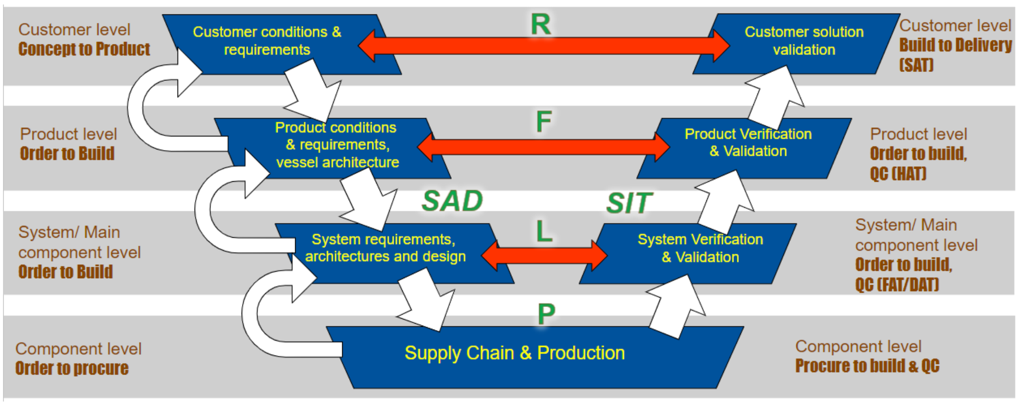


Figure 4.3: V model of the RFLP method created by Damen Shipyards (2018)

4.3. Ship design process at Damen Shipyards

Damen Shipyards is a family-owned business that was established in 1927. In the past 95 years, they have built and delivered over 6000 ships. Damen is famous for building series of standardised ships but the portfolio can be separated into three types of ships: Fully customised (one-off) vessels, semi-customised ships, and standard build small series (Wesselman, 2017). Standardised ships, such as the tugs, are based on a "template". The template pre-defines certain modifications meaning there is not much engineering needed after the first ship, focusing on an efficient building process instead of the single product result. However, this template mostly standardises the vessel type and hull, whilst the systems within the vessels are less standardised and vary per vessel and vessel type (Treur, 2020).

For the design, the four stages of concept, system development, system production, utilisation & support, and retirement are evaluated. The breakdown of the system analysis is shown in Figure 4.4. The goal at Damen is to use systems engineering for future designs. An example of the application of systems engineering at Damen Shipyards is the NAVAIS project. NAVAIS is an abbreviation of New, Advanced and Value-added Innovative Ships. It focuses on merging a standardised and modularised approach with customer-tailored vessel solutions, by balancing requirements with the minimal amount of design, development, production and service efforts (Treur, 2020).

Looking at the current implementation of systems engineering at Damen Shipyards, it can be concluded that even though the ambition is there, designers in practice often use methods that suit their case and the design approaches are not as laid out as presented in the description of systems engineering.

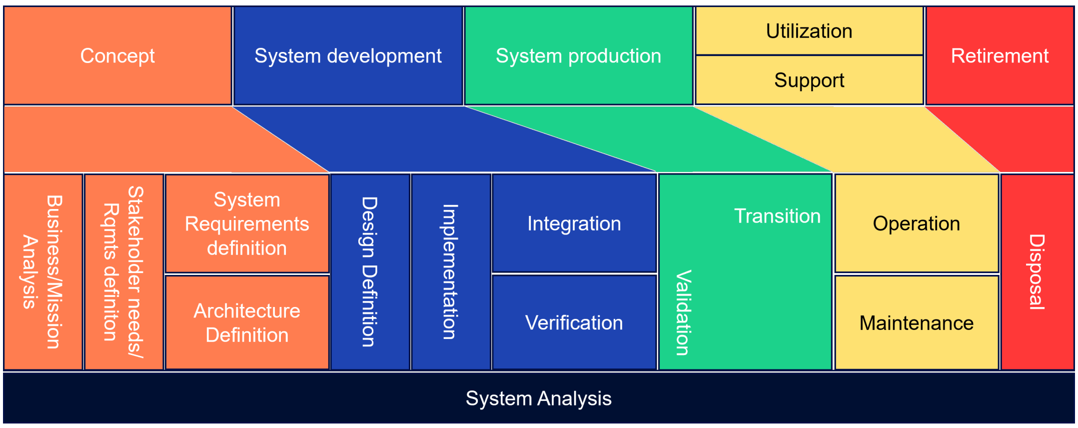


Figure 4.4: Technical process of system analysis at Damen Shipyards (2022)

4.4. Circular design approaches for consumer goods

In this section the second sub-question will be answered; *What are the circular design approaches for consumer goods?* Design approaches are the ”guidelines” on how to create a design that meets the values of circularity set out by the various frameworks as discussed in section 3.1. The focus is on consumer goods since the use of circular design approaches is already a more common practise there. First, an overview of all design approaches will be given, after which the presented design approaches will be linked to the 10R framework.

4.4.1. Overview design approaches and strategies

According to the European Commission (2020a), 80% of the environmental impact of a product is determined during the design phase. Therefore circular design approaches are very important in the move towards a circular economy. During the design phase material choices are made and it is determined whether a product will be able to be used for 1 day or maybe 30 years. These types of considerations have a significant effect on for example the circularity of a product; The design determines if and under what conditions products can be recovered (Boorsma et al., 2022). H&M Group (2021) also states that products that are designed to have long durability, are often not scoring well in terms of recyclability. This leads to trade-offs between creating products that can last a long time, and products that are easy to recycle at the end of their lifetime.

Moreno et al. (2016) have mapped out many design approaches related to designing products where circularity is taken into account. Often this type of design is referred to as Design for Sustainability (DfX). A taxonomy of DfX design approaches based on their research and complemented with additional sources is included in section B.1. The table shows a sustainable design approach, to which multiple circular design strategies are added. To each design strategy, multiple design focuses are connected and to every design focus then multiple methods and tools are related. From this analysis, it can be concluded that many different design approaches and strategies can be followed where some have overlapping interests. den Hollander (2018) states that a product’s lifetime is often seen as the time during which a product is functional. However, functionality is an insufficient criterion because products are discarded while still in perfect working order and products can be temporarily out of order without the need to be discarded immediately. A more extensive explanation of den Hollander’s theory is added in section B.1. Maintenance is a strategy that is not explicitly mentioned but is very important to enable different circular approaches. Maintenance ensures that products or systems are kept in good condition. Maintenance can be a combination of multiple strategies such as repair and repurposing. Systems and products that are well maintained will be more suitable for reuse, refurbishment, remanufacturing, etc.

4.4.2. Design approaches and the 10R Framework

As already explained in Figure 3.1.1, the 10R ladder shows the ambition level of circular strategies. There is a priority distribution of 10 circular economy strategies and aiming for the highest possible level is the goal of the framework. In Figure 3.4a, short explanations were already given for all 10 circularity strategies, but a more in-depth explanation will be given below, in the order from the highest to the lowest priority of the strategies. The first three; refuse, reduce and reuse, focus on the cut down on raw material usage by use of design for reduction of resource consumption (Cramer, 2020)(Bocken et al., 2016). The design focus for the strategies Reuse, Repair, Refurbish, Remanufacture and Repurpose focuses on product life extension. For Recycle and Recover, the focus is mostly on designing for resource recovery/multiple cycles. The categorisation is visualised in Figure 4.5.

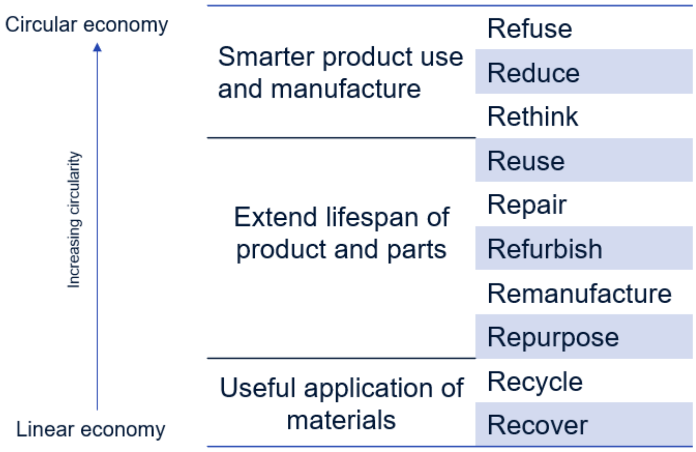


Figure 4.5: Visual of the 10R model and design focusses based on Cramer (2019)

R0 - Refuse

By refusing, the use of (raw) materials can be prevented. The focus is here on unnecessary and unsustainable products by coming up with solutions that maximise the usage of fewer goods (Lombard Odier, 2010). Refuse is often listed as the R0 because this value retention option has zero use and impact (Reike et al., 2022). If you separate consumers from producers and designers, the focus for consumers should buying fewer (useless) products, whilst product designers can refuse the use of specific (hazardous) materials.

R1 - Reduce

Whereas refuse is about preventing (raw) material use, reduce focuses on decreasing raw material use (Cramer, 2022). For consumers, this means that products should be used less frequently or be used with more care (Reike et al., 2022). For designers, the focus should be on using less material per unit of production.

Vezzoli and Manzini (2008) have multiple focus areas to minimise the use of (raw) materials/resources such as material consumption, energy consumption, and toxic and harmful resources. Minimising material can be done by minimising the material content of a product, minimising scraps and discards, minimising or avoiding packaging, minimising material consumption during usage, adopting flexible material consumption systems, and minimising material consumption during the product development phase. To minimise energy consumption, the aim should be to minimise energy consumption in every step of the process from product development to production and usage. Something that can help here is to enable variable energy consumption to follow demand fluctuations. Lastly, to minimise the toxicity and harmfulness of resources it is important to select non-toxic and harmless materials and energy resources. All materials have an impact on the environment, some more than others. Materials can be compared by the use of several methods such as LCA.

Taking these important focus areas into account, the materials to be chosen can be either from a primary or secondary/recycled resource. Primary resources are the so-called ”raw materials” and can be divided into renewable primary resources and non-renewable primary resources. Secondary raw materials are derived from scraps and discards of the production-consumption system, processed at either the pre-consumption or post-consumption stage. A pre-consumption resource is a waste that was discharged in a production process, whilst post-consumption resources are acquired from goods and packaging that were already used by the end-user. To reduce the use of raw, primary resources, the aim should be to design goods with a focus on secondary resources.

R2 - Redesign

By redesigning a product with a view to circularity principles, the environmental impact of a product can be reduced (Lombard Odier, 2010). This value retention is very important in the move towards a circular economy, since the aim is to have only circular products, current non-circular products will have to be redesigned. Clark et al. (2009) address this and state that the improvement potential can be relatively easily determined since the market and manufacturing information of the existing product is available. The process of redesign should involve a project team that harnesses outside expertise to incorporate sustainability aspects into products as well as company employees to provide valuable insights. To choose products for redesign, the focus should be on the potential of the greatest impact that is simple and does not require too much time that is in line with the company goals. To see the advantages of redesign, the redesigned product should be compared to the original product. There is not one design strategy for redesign, but during redesign, all strategies related to value retention should be considered.

R3 - Reuse

When a product is used by a second consumer without needing any adaptations and it works 'as new', we call it reuse. In society, these products are called "secondhand". So the product fulfils the same purpose without any repairs (Reike et al., 2022). The strategy that fits this value retention best is "design for easy maintenance, reuse, and repair". The focus on reuse is amongst others addressed by Bocken et al. (2016). It is stated that circular business models can make sure products and materials are reused. Reuse slows down the flow of materials from production to recycling. The durability of a product is closely related to its reliability (C. Bakker, den Hollander, et al., 2014. Both technical reliability and perception of reliability are important. The perception of reliability can lead to different technological solutions than real reliability when the consequences of failure start to show. Looking at den Hollander (2018), design for emotional and physical durability are the two design strategies that match this value retention. To design for emotional durability, the design needs to aim for a product that will remain wanted by users over a long period of time, whilst physical durability is the capacity of a product to endure wear and tear, stress, and environmental deterioration while maintaining the ability to perform all the intended physical functions for an extended duration. Emotional durability can be achieved by designing products for "attachment" or "detachment" (Chapman, 2015). Creating either a strong emotional connection to the product or on the contrary creating no emotional connection, creating low expectations and thus users will perceive it in a favourable way. These two strategies also play an important role in repair, since products will be repaired as long as they manage to remain wanted and obsolescence is avoided.

R4 - Repair

The aim of repairing a product is to bring it at least back to working order and preferably make it as good as new, often by replacing broken parts (Reike et al., 2022). By repairing a product its lifetime can be extended. Consumers can either repair a product themselves, send it to a repair company, or businesses that recollect products to their repair centres. A product can be designed to have "planned" repairs during its lifetime, but there can also be ad-hoc or "emergency" repairs. The design strategy of design for repair/refurbishment fits this value retention best. According to C. Bakker, den Hollander, et al. (2014), everything is repairable in countries with low wages, but in areas with high wages maintenance and repair are expensive and consumers have enough money to replace the cheap products instead of repairing them. Design for maintenance and repair is the most logical strategy when the supplier of the product benefits from the repair. Often this is the case in business models where the supplier is assumed to be the owner of the value proposition. Another case where consumers are often tempted to repair products is when they are emotionally attached. This is not important for every product, but an example is the favourite stuffed animal of a little kid, which no matter how damaged, it will not be thrown away. To repair products with ease, Kimura et al. (2001) suggests that appropriate product modularisation can help. The products can be divided into different modules and each module can be repaired/replaced separately. The determination of size and content of each module is complicated to decide and are determined by multiple factors such as cost, functional independence, standardisation, ease of maintenance, etc. According to van Nes and Cramer (2006) it is a general principle that the environmental impact of consumption patterns can be reduced by an extended lifetime of products. However, this is not always true and it should be determined whether the longevity of products is environmentally desirable or not. Repair is separately addressed by den Hollander (2018). He states that repair, is the correction of errors in an obsolete product, in order to bring the product back to working condition. Where repair is considered a part of maintenance. To ease maintenance, principles such as standardisation, modularisation, interchangeability, etc. are mentioned to be important.

R5 - Refurbish

Whilst during repair some broken components are replaced, in refurbishment ”the overall structure of a multi-component remains intact, while many components are replaced or repaired, resulting in an overall “upgrade” of the product” (Reike et al., 2022). This means that an older product can be updated to the state of the art by newer and/or more advanced components (Stahel, 2016). For this indicator, design for refurbishment is the desired strategy. Since during refurbishment products are updated, this is not applicable to all types of products. Products should be designed such that components can be replaced, same as for repairing. When updates are designed, it’s important that these modules are compatible with the current product and easily changeable (Sumter et al., 2018). den Hollander (2018) also mentions refurbishment, where refurbishment is defined as turning an obsolete product back into satisfactory condition. Also, den Hollander (2018) notes design for upgrading, and as upgrades are a part of the refurbishment, this design strategy should also be mentioned here. Where with an upgrade, the functional capabilities of a product are enhanced relative to the original product. Here, also interchangeable components are important to ease the upgrade, just like for repair. An example of a company that recently used refurbishment is the Nederlandse Spoorwegen (NS), the principal passenger railway operator in the Netherlands. They aim to have implemented circular purchasing, maximum reuse of materials and zero waste at their office, workshops and trains by 2030 The optimisation of material use means thorough maintenance, repair and a life extension program (NS, n.d.). An example is the double-deck VIRM that needed modernisation. The NS managed to refurbish and reinstall 86% of the parts in the train. Another 13% will be given a second life elsewhere, coming to a total reuse of 99% of the materials.

R6 - Remanufacture

During remanufacturing ”the entire structure of a multi-component product is disassembled, checked, cleaned, and when necessary, replaced or repaired in an industrial process (Reike et al., 2022)”. Whereas by refurbishment a product is often updated to a newer standard, remanufacturing is more about getting a product back up to its original state, as if it is new. An important characteristic of remanufacturing, seen from an environmental point of view, is that it preserves the embodied energy, also called emergy, that was used to create the components for their first life (King et al., 2006). Remanufactured products are said to require only 20-25% of the energy compared to new products. The design strategy of design for remanufacturing and dis- and re-assembly fits best here. This strategy is explained by Hatcher et al. (2011). The outcome of remanufacturing is a product with both new and reused parts. the product needs to be designed with a focus on remanufacturing steps such as disassembly and cleaning with the (obvious) goal of enhancing remanufacturability. To achieve this, the designer has to consider every remanufacturing step and the effect of the design on them. Even though it is in theory the most effective method to consider each aspect of remanufacturing separately, in practice it may be discouraging for a designer. Still, the design for remanufacturing is typically described in these terms. A product that’s designed with a focus on remanufacturing, must be easy to take apart and reassemble. Also, the type of connections between parts plays an important role in this. For a company to be a good candidate for remanufacturing, the products must have five qualities: 1) Circulation of previously used products in opposite direction, 2) Consumer appetite for refurbished merchandise., 3) Long-lasting, valuable components, 4) Technological consistency, and 5) Capability for future enhancements.

R7 - Repurpose

Repurposing gives the material a new life cycle by reusing discarded goods or components that are adapted for another function (Cramer, 2022). For example, the NS converted multiple offices, and the existing materials and train equipment were reused where possible. Old train floors have become furniture, the glass train walls are now repurposed as partitions and the ceiling panels have been turned into desks. Maas (2020) developed practical guidelines for circular product design focusing on repurposing. The aim of designing for repurpose is to maintain as much product value as possible over time by incorporating ”infinite re-use of product parts for other products during the design of the first product” (Maas, 2020). The guidelines are divided into 3 parts:

1. The starting point where the designer needs to find out/know when to change, what there currently is, and predict future changes.

2. The research into product opportunities where the designer needs to be certain by predicting what products will be required once the original product becomes obsolete.
3. The redesign phase is where a product is redesigned with the aim to be able to reuse the product in subsequent products.

According to Aguirre (2010), it is possible to design for repurposing also when the future requirements are not sure since the designer determines the stage for possibilities rather than controlling or directing the eventual repurposing. A good example of design for repurpose are the Nutella jars, designed by Ferrero, which after being emptied of Nutella, can be used as drinking glasses as shown in Figure 4.6. den Hollander (2018) states that a new term to replace repurposing is recontextualising. Recontextualising is the "term for use of an obsolete product (or its constituent components), without any remedial action, in a different context than it was used in as it became obsolete" (p. 36).

Figure 4.6: The repurposing of a Nutella jar as a glass (Aguirre, 2010)

R8 - Recycle
The purpose of recycling is to salvage material stream with the highest possible value, preferably upcycling instead of down-cycling the materials (Moreno et al., 2016). During recycling, discarded materials are collected, sorted, processed, and then used in the production of new products (King et al., 2006). Recycling plays an important role in reprocessing materials so they can be used again (H&M Group, 2021). For this, it is important that products are made of materials that can be recycled later after a product has been used extensively. This way a supply of feedstock can be secured and products can again be made out of recycled materials, this closes the loop. Even though recycling is at this moment the most commonly used waste avoidance strategy, designers are often hesitant to use recycled materials due to the uncertainty in quality and/or supply standards (King et al., 2006). Recycling can be divided into two different routes: Closed-loop recycling and Open-loop recycling (Vezzoli and Manzini, 2008). In closed-loop recycling, the system recovers materials that are used instead of primary raw materials in the same product/components that they were used in before. In open-loop recycling materials are recycled by producers who did not manufacture the original product. To be able to recycle, it is important to know the configuration of products to identify materials and separate them. Therefore design for recycling impels the producer to design to facilitate recycling.

R9 - Recover
The lowest priority level is energy recovery by incinerating waste (Cramer, 2022). This is common practice when materials have been recycled multiple times and their characteristics are not satisfactory anymore for any application (Vezzoli and Manzini, 2008). However, not all materials are suitable for incineration since they might emit dangerous substances during incineration or might hinder the incineration. Examples of these materials are glass, metals, concrete, and ceramics. When designing for incineration, it is important to avoid the use of heavy metals in things such as paint, fire retardants, colouring pigments, etc. but also be sure materials are suitable for undergoing combustion without emitting dangerous substances. Also, high-energy materials are preferred to be used for incineration.

4.4.3. Conclusion on design approaches for circularity
By connecting the different design strategies to the 10R framework, it can be seen that every R-value is supported by a design focus and sometimes even multiple. Even though focus points are mentioned, there is not a clear step-by-step guide on how to apply these focus points. As stated before, the choice was made to include the framework presented by den Hollander (2018) into the 10R framework because the 10R framework shows a clear distinction for prioritising design strategies and also includes the inflow of materials in the first three pillars of refuse, reduce, redesign, which den Hollander does not mention. Also, recycling is excluded from his design for preserving product integrity. Additionally, the design approaches presented here have a focus on consumer goods and are not yet applied in ship design approaches. To see how to connect these two aspects, in the next section the differences between the ship design approaches and circular design strategies will be set out.

4.5. Differences in design strategies for shipbuilding and consumer goods

In this section the third sub-question will be answered; *What are the differences between design approaches for normal consumer goods and ship systems?*. To stress the need to apply circular design strategies that are used for consumer goods in ship design, the differences between ship design strategies and consumer goods design strategies will be set out. According to Ashby and Johnson (2003), there is a difference between engineering design, under which the art of ship design could be seen, and industrial design which involves the design of consumer goods.

First of all, engineering is systematic; it follows well-established and commonly accepted procedures, whilst industrial design does not. Industrial design is strongly influenced by fashion and advertising. Industrial design is less about functionality and efficiency, but the focus is more on qualities such as form, style texture, etc; the ones that cannot be measured. Engineering designers often use formal guidelines such as ISO standards whilst industrial designers have representations which are imprecise, ill-defined and less established (Pei et al., 2011).

The difference is shown in Figure 4.7. Pei et al. (2011) also states that engineering design is more about associating models with engineering principles, production issues, and functional mechanisms, while appearance and usability are the most important focus points for industrial design. The fact that industrial design is more vague can also be seen in subsection 4.4.2 since the design strategies presented in this section don't go into detail or have a guideline on how to get to a sustainable design, whilst the ship design strategies as presented in section 4.1 show a clear approach. Engineers often argue that a product is automatically beautiful when it is functional, examples are bridges and aircraft, whilst industrial designers argue that design is an art. According to Pei et al. (2011), design applications such as shipbuilding focus on producing technical details for manufacturing based on cost, quality and performance whilst consumer good design is focused on making sketches and after that physical models which are based on aesthetic attributes.

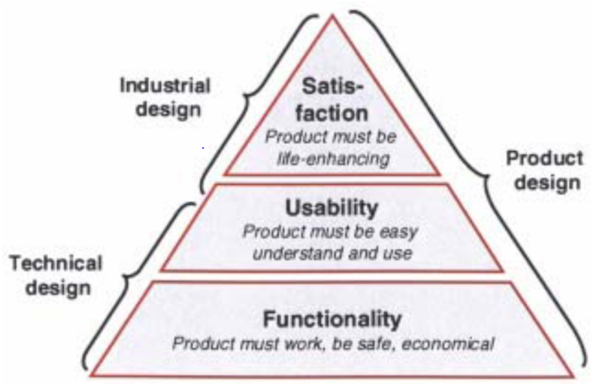


Figure 4.7: The requirements pyramid (Ashby and Johnson, 2003)

The need for clear guidelines and standards is also bigger when looking at ship design since a vessel is way larger and more complex than consumer goods. Inside a ship, many systems, subsystems, components and parts are present, whilst consumer goods such as chairs, tables, etc. often consist of way fewer parts and components. Consumer goods such as these are often present inside a vessel and need to be integrated into the design of the complete vessel. Another thing designers for consumer goods consider during the design phase is the mass production of products, whilst ships are often one-offs or maybe a series of multiple vessels, but never thousands of the same product.

van Nes and Cramer (2006) state that the product lifetime of consumer goods is not a predetermined design criterion, but a result of user decisions. In shipbuilding, there is the requirement that a ship will last for often at least 25 to 30 years (Mikelis, 2019). However, this does not mean that the ship does not undergo any repairs/refurbishments in these years. Also, during the in-house research, it turned out that systems and components on board a ship are often not designed for a specific lifetime, but chosen based on reliability and experience (J. Kalis, personal communication, April 3, 2023). Even though in this case it might not be a direct requirement, with a focus on reliability and experience systems and components are still chosen with the focus on a certain lifetime since the aim is to have the highest reliability of every component.

As stated before, consumer products are designed with a focus on appearance and usability, but it should also be mentioned that consumer products often follow trends and fashion and are therefore subject to becoming obsolete. Consumer products and their lifetime are strongly influenced by user behaviour and wider socio-cultural influences (den Hollander, 2018). Ship design is not influenced by the type of colour that is in fashion at this moment but is mostly cost-driven by the market and client demand. Ships can also become obsolete, but this will happen due to a drop in the world market. The shipping industry is however strongly influenced by consumer products since, for example, container ships transport consumer goods, bulk carriers carry raw materials for consumer goods, etc. It can be said that both markets are client-driven, but the maritime sector is influenced by the world market, having a bigger distance to one specific customer, whilst consumer goods are dependent on a way smaller groups of people buying specific products, having a direct line with consumers. So since the markets are influenced by different sizes of groups, the influence of everyday people is different. For example a box of shoes; as a consumer, you can choose at which shop you want to buy your shoes, consisting of certain materials and having a certain look. This box of shoes will probably be shipped from the production country to the country you live in per ship. Which shipping company, how much emissions the ship emits or what the ship looks like is not of choice for the consumer that buys the shoes, but is chosen by the shoe-selling company. One consumer can not influence this decision, but if enough consumers want the shipping company to for example have fewer CO2 emissions, the shoe-selling company might go looking for such a shipping company, whilst if a consumer wishes to have sustainable or circular shoes, they can just choose a different company to buy the shoes from. More and more people see the need to choose more sustainable products, driving first consumer products in this direction, and after this the shipping industry. Nowadays, the label ”sustainable” is becoming more and more of a trend and selling point, driving designers to apply sustainable principles such as circularity in their design strategy (Rosmarin, 2020).

For a shipbuilder to design a ship whilst keeping sustainability in mind, the client needs to be willing to pay for the sustainable ship. The client is then again dependent on for example retailers of products, which are again dependent on consumers. Retailers and consumers are often not on the same page regarding sustainable shopping. First Insight (2022) found that retailers often underestimate the willingness of consumers to pay more for sustainable products and brands, and retailers also wrongly assume that consumers value brand names higher than product sustainability since consumers rank product sustainability over brand name. With these misconceptions, the demand for sustainable shipping might be lower than it could be if consumers had a direct say.

4.6. Conclusion on combining design approaches for circularity and ship design

It can be concluded that the biggest difference between ship design approaches and circular design approaches is the need for a clear and structured design method for ship design, which is less important for consumer goods. But also the other differences such as the influence of fashion and mass production on the design of consumer products are important to note. To include circularity, the systems engineering method will be chosen in combination with the ten design methods complying with the 10R framework. Because systems engineering follows a clear step-by-step approach, circular design principles will be included in the steps of systems engineering. To include these principles, the differences between the design methods should be kept in mind and where possible the circular principles should be added in every step of systems engineering. To see how circular a product is, or in other words, which R-value is important for a product or system, the key indicators to asses this will be set out in the next chapter. These key indicators can be used to see which of the 10R design strategies the focus should be when designing a system. After that, the implementation of the circular design approach into the ship design approach will be shown in chapter 6.

5
Key indicators

In this chapter, the aim is to answer the fourth sub-research question: *How do key indicators influence the circularity of a system?*. Key indicators will be identified that determine the circularity level of a system. After that, the influence of the key indicators on the different circularity levels will be elaborated upon.

5.1. Identifying key indicators

In this section the first sub-sub-question will be answered; *What are the key indicators of a system to evaluate the current focus level on circularity?* To see what the current level of circularity of a system is, and what design strategy needs to be used when (re)designing a system with a focus on circularity, the key indicators are important to see the purpose of the design. In this chapter, multiple system properties will be identified and explained. These system properties are derived from the addressed system properties in the ten circular design strategies that were described in subsection 4.4.2 and the information required to fulfil the MCI calculation as presented in section 3.3. As explained before, the 10R framework can be divided into three different stages;

1) The design stage, where the inflow of (raw) materials can be reduced.
2) The time during the product's lifetime when the aim of the circularity indicators is to extend the lifetime as long as possible.
3) The end of the product's lifetime in its current function, where the materials in the product need to find the most useful application.

In this section, different key indicators, also known as system properties, will be set out and their importance during each stage of the lifetime of a system will be set out. The section will start with material choice since this is the main driver for the origin of the inflow. Then, lifespan and use frequency will be elaborated upon which are indicators to calculate the value of the utility (X). After this, cost, modularity and reliability will be discussed which all are, together with material choice, the drivers that determine what happens with the product at the end of life. Finally, an example will be given of how the indicators can influence a design.

5.1.1. Material choice

The material processed in a system or product has a big influence on the circularity of a product. When measuring circularity with for example the CTI or MCI tool, material choice is the main thing which is assessed. As explained in Equation 3.2.1, a distinction can be made between the inflow and outflow of materials, where the inflow can be separated into virgin or non-virgin materials. Non-virgin materials can be either reused, recycled, refurbished, etc. and virgin materials are materials which have not been used before. The outflow is also separated into different options corresponding to the R-values of the 10R framework. Often, a distinction can also be made between the potential recovery, and the actual recovery since not all materials that are recyclable are actually recycled in practice. The goal for every material, in a one hundred per cent circular economy, should be an inflow of non-virgin materials and an outflow of one hundred per cent actual recovery with an outflow of preferable reuse, but all R's and up and until recycling would be an acceptable form of recovery. Also, hazardous materials are important to note here, examples of these are asbestos, lead, cadmium, etc. because they need special treatment but this does not mean they cannot be seen as circular materials. Lead for example can be recycled for 99% (Ecobat, n.d.).

In some of the measurement methods, a distinction is made for critical materials. These critical materials were identified by the EU as being the materials that have a high economic importance for the EU and a high supply risk (European Commission, 2023a). These materials should be avoided as much as possible since they are not easily renewable. However, when the materials can be kept in the loop, it might not be a bad idea to keep on using them, but this is not something the measuring methods take into account.

To conclude, the material is one of the most important, if not the most important indicator of the circularity of a product. The inflow of (reused/recycled) material determines half of the circularity of a product, whilst the outflow of materials defines the other half. The type of material determines what will happen with the product at the end of the product's lifetime when material recovery becomes important: recycling or recovery, or even landfill. But also during the lifetime, a material needs to be repairable if repair, refurbishment, remanufacturing or repurposing is desired.

5.1.2. Lifespan

Lifespan or lifetime is a very broad term and it's hard to find one definition which describes all aspects of it. As said before, den Hollander (2018) proposes to define product lifetime in terms of obsolescence. This is because often a product's lifetime is equated with the time that a product is functional, but this is an insufficient criterion since products that still work are also discarded and products that are temporarily out of order are not directly at the end of their lifetime. Therefore, a distinction will be made between functional lifetime, economic lifetime and environmental lifetime. den Hollander (2018) also mentions social lifetime and aesthetic lifetime, but these are, as discussed in section 4.5, not as important in ship design as for consumer goods, therefore these will not be included here.

So, the end of a system's lifetime can be determined by economic, functional or environmental aspects. Regarding economic lifetime, it's often said that the economic lifetime of a product has passed the point where replacement is cheaper than keeping the product in service (den Hollander, 2018). The same goes for the environmental lifetime; there is a break-even point where the replacement of a product with a new one, which provides the same function, results in less overall environmental impact (Vezzoli and Manzini, 2008). The end of a product's functional or physical lifetime is the moment when a product can no longer fulfil its function, or this function is no longer needed.

The total lifetime of a product is a combination of these three factors (economic, environmental and functional) and can end when the lifetime of one of the three subjects is reached. So the complete definition of a product's lifetime is: "the duration of the period that starts at the moment a product is released for use after manufacture and ends at the moment a product becomes obsolete beyond recovery at product level" (den Hollander, 2018). The end of a product's lifetime can be influenced by many factors such as damage caused by accidents, the shortage of repair parts, newer, better products which can not be integrated into existing products, requirements from classification, and many more (Kossiakoff et al., 2011)(Vezzoli and Manzini, 2008).

Lifespan is an important factor when looking at circularity because by making the lifetime of a product's lifetime as long as possible, the resource loops are slowed down, which is one of the aspects of circularity as explained in section 3.1. Lifespan can be a good indicator to see which design strategy is in line with the 10R framework a designer should focus on. When the lifespan of a product is known to be short and nothing can be done about that, it is important to focus on a strategy where recycling can be ensured. If a product is known to have a long lifetime, it is important to ensure this lifetime will be fulfilled by designing for reuse and repair. An example of how lifetime can be used to determine a design focus will be given in subsection 5.1.7. Lifetime can also help determine the current circularity level of a product since then a product is still in its desired economic, environmental and functional lifetime, chances are high that a product will be reused, whilst when one of the three aspects might be at the end of a lifetime, repair, refurbishment or even recycling might be the desired destiny of a product.

5.1.3. Use frequency

Use frequency is important in a circular economy since, while still meeting the demand for their performance, any product that is used more intensively (than other, comparable products) results in a reduction in the actual number of those products at a given time and location; this also determines the reduction in environmental impact depending on a number of factors (Vezzoli and Manzini, 2008). Also, the use frequency might impact the length of the lifetime of a product, since for some products lifetime is defined in absolute time, for example, usage hours. So if the product is used more often, these hours are finished earlier and the product might need repair/replacement earlier than the same product with a lower use frequency. The use frequency is important to keep in mind during the design phase, because more intensively used products are more exposed to wear and tear, which might result in the need for repairs (van Nes and Cramer, 2006). The combination of lifetime and use frequency is often referred to as utility, which compares how long and intensely a product is used to other an average product of the same type. How lifetime and use frequency can influence the design focus is explained in subsection 5.1.7. So use frequency is important to take into account during the design process and will also have an influence on the R values which play a role during the product's lifetime.

5.1.4. Cost

Even though a product can be designed with the least amount of raw material, be easily repairable and recyclable in the end; if the cost of every step is too high, the product will be disposed of instead of repaired, remanufactured or recycled (Vezzoli and Manzini, 2008). If also incineration is too expensive, dumping in landfills is often the option to go to. An example of such decisions is shown in Figure 5.1. So, cost has a big influence on the economic lifetime of a product. When designing a circular product, it is very important to keep in mind the cost of every R-value to make sure the highest value that is physically and environmentally feasible is achieved, but that is also economically achievable. The process of finding the most cost-effective option for retaining or disposing of a product is called the life-cycle cost analysis (Asiedu and Gu, 1998). Cost plays an important role throughout all the stages of the life cycle; from design to disposal. To map all costs involved in a product's lifetime, the concept of the total cost of ownership (TCO) can be used (Ellram, 1993). TCO involves the identification of major cost elements associated with key purchases. This can help users choose between products which might be more expensive when purchasing but have low maintenance costs or products that have low purchasing costs but higher maintenance costs. In the case of circularity, this might help to choose for circular, thus reusable, refurbish-able or recyclable products which can at the end of life be sold to other users, or repair/ recycling companies. In this case, retaining a high economic value during the product's lifetime is key in order to win back as much money as possible (Boorsma et al., 2022). An example from another industry using this principle is the automotive industry where Volvo aims to use the circular economy principles to generate 2.5 Mtons of CO2 savings and 1BSEK of cost savings by 2025. To achieve this, they have defined various actions such as producing their products with energy and material-efficient technologies, pioneering new circular solutions and designing their new generation of products, packaging and services according to the principles of a circular economy (Volvo Car Corporation, 2022). It can be concluded that cost plays a role during the design stage, lifetime and at the end of a product's lifetime.

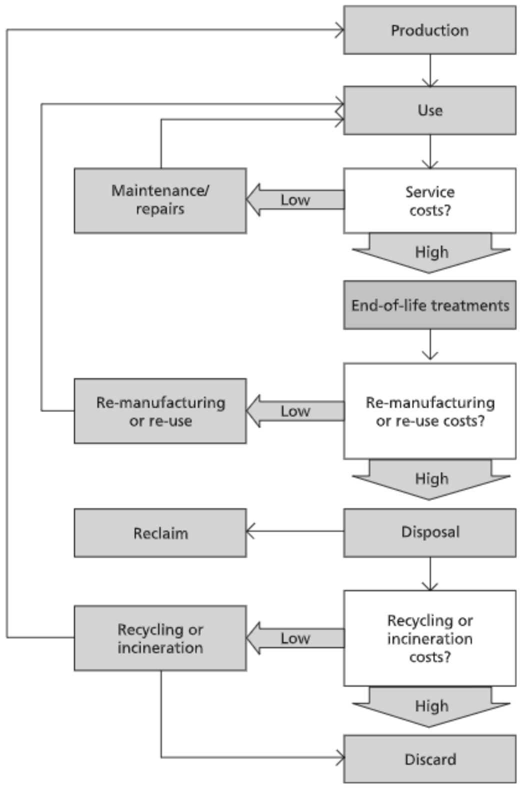


Figure 5.1: Disposal costs and prospects (Vezzoli and Manzini, 2008)

5.1.5. Modularity

Modular design means that a ”system is defined using modules which can be interchanged in the design with other modules” (Treur, 2020). One of the goals of systems engineering is to reach a high level of modularity in order to make interactions and interfaces as uncomplicated as possible (Kossiakoff et al., 2011). Kimura et al. (2001) identify five factors to determine modularisation: standardisation, functional interdependence, cost, ease of manufacturing and ease of maintenance.

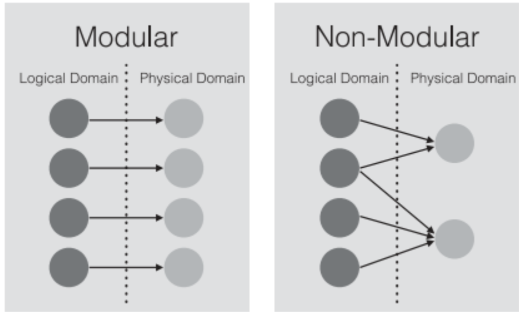


Figure 5.2: Architectural view of modularity (Efatmaneshnik et al., 2020)

Four of these factors apply to physical modularity, but maybe more important is functional modularity. ”Functional allocation” is the term used for subdividing a system into modular building blocks. By identifying the influence of one component on the rest of the components and systems, functional modularity can be assessed. Because the terms module and modularity are widely used but with different meanings, Efatmaneshnik et al. (2020) propose a definition for the term module: ”a segment of a system with a distinct boundary that relates to a particular nonfunctional requirement(s) of the system”. So a group of parts/subsystems with a physical or notional boundary which is detachable. This detachability can be either physical or national, and by this detachability, the module has a nonfunctional utility for a system, a stakeholder or a life cycle stage. A visual representation of this definition is shown in Figure 5.2. During the design phase, it is important to design products as circularly as possible, this way the other R-values during the product’s lifetime will be easier to execute. If a product is modular, the repair is way easier and probably cheaper than when the whole product needs to be taken apart to repair a small part. Also, when a product is designed in such a way that it can be easily dismantled and different materials can be separated, recycling will be easier. So modularity is important to keep in mind during the design phase and can play an important role in the level of circularity during the product’s lifetime and at the end of the lifetime.

5.1.6. Reliability

Reliability is closely connected to durability. Producing something with a long lifespan means it is designed for durability (C. Bakker, den Hollander, et al., 2014). The probability that a product is no longer able to fulfil its function, is the product’s reliability. To determine the reliability of a product consisting of several parts, the multiplication of the respective reliabilities is required. This can be seen as technical reliability, but the reliability perception is also very important and could lead to a different technical outcome. According to C. Bakker, den Hollander, et al. (2014), an example of reliability perception leading to a different technical outcome is the copying machine. Back in the day, copying machines used to be as large as five to six refrigerators. Even though they functioned well for months, after a few months a paper jam occurred. To fix it an engineer had to come and perform maintenance, clean the machine and with that restore its function. This caused the machine to be out of order for two days. With the further development of copying machines, the machines got smaller and around the 1980s producers realised it would be easier and preferable to have users fix the defects of the machine such as paper jams themselves. This resulted in a technological illogical effect; users accepted that the machine would stop working more often, say once a week, as long as it took them only a few seconds to open the machine and fix the paper jam by pulling out the blocking piece of paper. Users even perceived this new machine as more reliable than its predecessor.

Some cars also have a reputation for reliability and endurance, such as the Rolls Royce which is known for its traditional chic sturdiness. Whilst for example the Fiat 500, Volkswagen Beetle and Mini are also classics, but few originals are left. Another good example is Porsche; the majority of all ever produced are still on the road (C. Bakker, den Hollander, et al., 2014). Reliability mostly plays a role during the product’s lifetime, especially in the case of reuse (R3), because reused, second-hand products must also be reliable for a second owner.

5.1.7. Example of key indicators influencing design

A basic example of using product properties to identify the desired design strategy is the Circulator Guide developed by H&M Group (2021). The Circulator guide presents four steps to help fashion designers choose a circular design strategy. Step 1 is to get to know the customers' needs and expectations to bring relevant products to the market. This way optimising orders and minimising excess inventory which is crucial to maximising resources in a circular economy. Secondly. the product purpose needs to be defined. By use of two indicators; the Life span of the product ("How long will this product be relevant for the customer?") and Frequency ("How often will the product be used by the customer?"), the product can be categorised into a light, mid or extensive use category. This process is shown in Figure 5.3. The method describes starting at a monthly user frequency for about three years and then going up or down the frequency axis. After this one can go left or right on the lifespan axis. This gives an indication for a light, mid or extensive used product, but based on the amount of wear and tear expected the categories can be changed. Also, products subject to a rental, subscription or multiple users will need to be moved up one category.

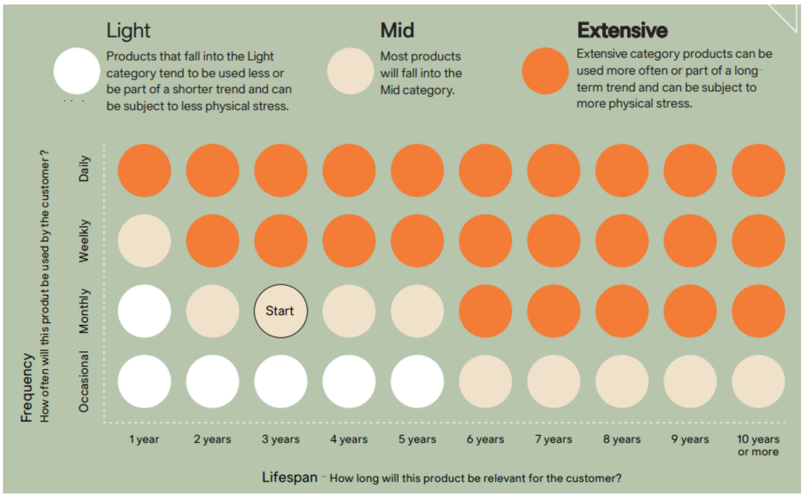


Figure 5.3: Defining a product's purpose based on lifespan and frequency of wearing (H&M Group, 2021)

Per product category, the importance of materials and design strategies is determined. The categories and their circularity level focus points are shown in Figure 5.4. By use of this, the importance of material footprint, durability and recyclability is determined and the designer is guided by this in terms of material choice. For a light product, the focus is on materials that are easy to recycle and have a lower footprint. For mid-category products, the priority is on materials with a lower environmental footprint, whilst also keeping in mind durability and recyclability, but to a lesser extent than for a light product. For extensive purposed products, the priority is to select materials with a low environmental footprint which are also durable. Recyclability is in this case also important, but to a lesser extent. The last step is to select the design strategy, where the aim should be to use at least three design strategies but the more the better. the design strategies to focus on are also shown in Figure 5.4. These design strategies show some overlap with the approaches addressed in subsection 4.4.2, but also some differences can be noticed. This once again shows that circularity is a vague concept where every organisation uses their own interpretation.

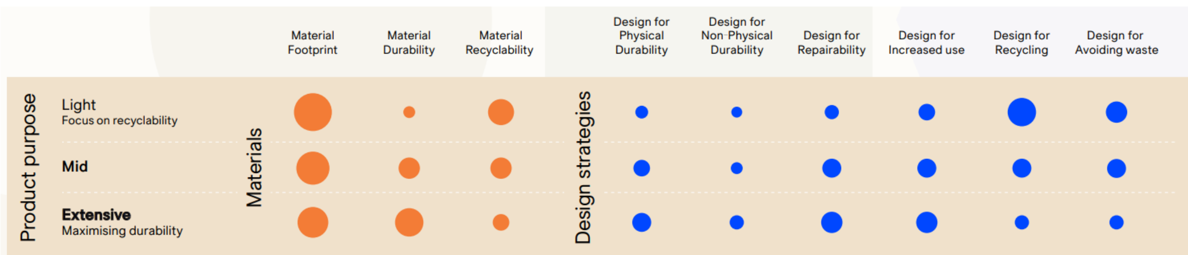


Figure 5.4: Product purposes and their importance in the level of materials and design strategies (H&M Group, 2021)

5.2. Linking key indicators to the 10R framework

In this section, the second sub-sub-question will be answered; *What is the influence of including circularity in the ship design approach?* As described before, the 10R framework can be divided into three different stages; the design stage, the time during the product's lifetime, and the end of the product's lifetime in its current function. This section will focus on using the key indicators to influence the circularity of a system at every stage. First, the design stage will be discussed, then the lifetime will be explained and lastly, the end of life will be discussed.

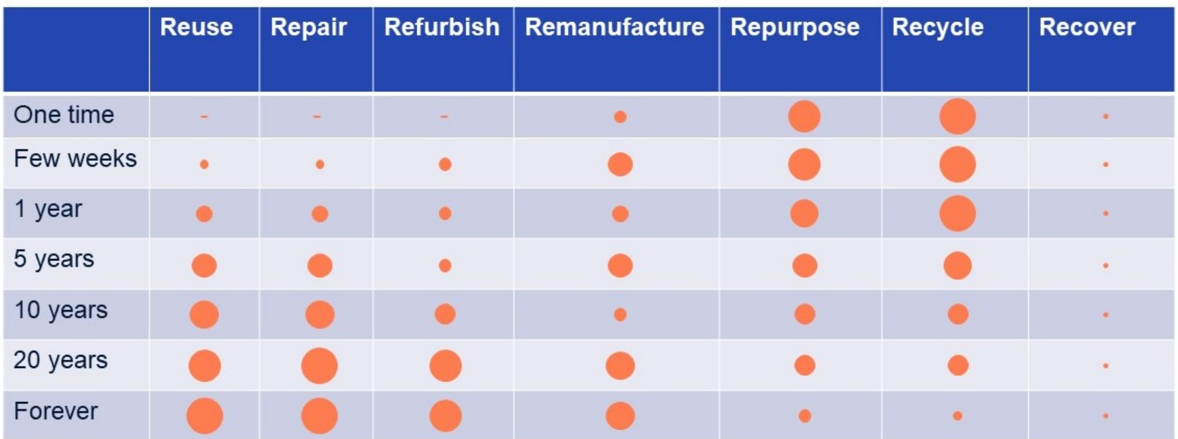
5.2.1. Design: Determining the design focus

The system properties of lifetime and use frequency (together utility) can help to determine the design focus in terms of the 10R framework. By looking at the required or expected lifetime, one can decide to optimise a design for, for example, reuse or recycling. The same can be said about use frequency; the more a product is used, the more it is exposed to wear and tear, which might result in the need for repairs. The decision for lifetime and use frequency depends on the requirement or desire set by a customer or client. It can also be that it is known beforehand what the lifetime of a product will be due to rules for example such as in the medical environment where everything needs to be sterile. Both key indicators will be linked to the R-values of Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover by use of circles. The size of the circle shows the influence of the certain lifespan on the R-value; the bigger the circle, the bigger the need for the design for that R-value.

Lifetime

As explained before in subsection 5.1.2, lifespan is limited by three factors; economic, functional and environmental lifetime. Whichever factor reaches its limit first will determine the end of a system's lifetime (in its current function and condition). Based on the lifetime requirements or expectations, it is possible to determine which design strategy regarding circularity should have priority during the design process. When a system or product will only be used one time, which could be for multiple reasons such as regularity requirements such as for medical supplies which can not be reused, it is already known that there is no need to extend the lifetime of the system by reuse, repair or refurbishment. The end-of-life processes such as repurposing or recycling become very important in order to retrieve as much value of the product as possible. The other way around goes for products which will have a very long lifespan such as 20 years or maybe even more. For these products, it is very important to ensure this long lifetime by designing for reuse, repair and refurbishment, whilst repurposing and recycling become a little less important, but are still relevant for when the product will reach the end of its lifetime to ensure material recovery of materials in the best possible way. For all lifetimes holds that recovery should never be a desired design strategy since this can not really be seen a part of the circular economy and can only be a last resort when other strategies are not possible anymore.

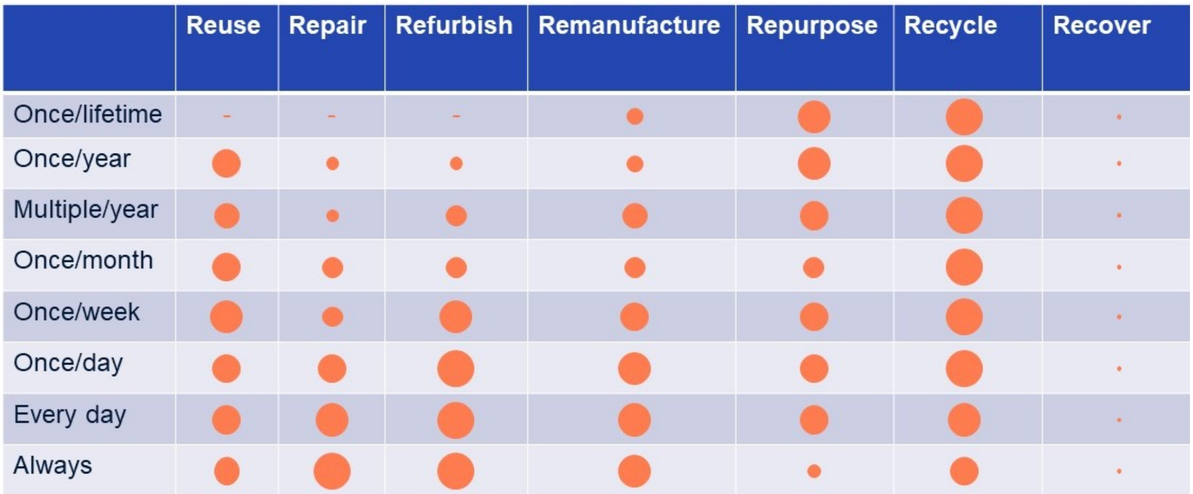
Table 5.1: The influence of lifespan on the different R-levels



Use Frequency

There is a big difference between a product with a lifetime of 20 years that is used once a year and a product with a lifetime of 20 years that is used constantly. Therefore use frequency plays also an important role in determining the design focus. If a product is used once per lifetime, this is kind of the same as a product that has a lifetime of only one time of use. So no lifetime-extending steps are needed. If a product is not used much such as only once a year, it will not wear and tear a lot, enabling reuse without repair and refurbishment, making these two less important. What stands out regarding use frequency is that it does not really influence the importance of designing for recycling; independent of the use frequency, recycling is always important since even though a product is used every day, at the end of its (unknown) lifetime, recycling is very important. For products that are used all the time, it is often important that they are working and updated at all times, stressing the urge for repair and refurbishment. Similarly to lifetime, recovery should never be a desired design strategy.

Table 5.2: The influence of use frequency on different R-levels



Utility

As stated before, the combination of lifetime and use frequency is called utility. The MCI method proposes a way of calculating utility by comparing a product to the industry average. However, the design focus of a product is not really related to the industry average but more about the absolute lifetime and use frequency. When the combination of the design focus needs to be assessed, for example for a product with a lifetime of 10 years with a use frequency of once/day, the average combination of both circles needs to be taken. This could mean that all design strategies become almost equally important, having to design for all circular strategies.

5.2.2. Lifetime: Reuse and repair during functional lifetime

If the design focus is on reuse and repair, the choice of the key indicators plays a very important role. A few choices in the design per key indicator can enable reuse and repair:

Reuse:

To enable reuse, every key indicator has a few aspects that a designer can focus on:

- Material choice: A material needs to be chosen that is durable and can be connected to other materials in a durable way. This means choosing the right material for the right job and avoiding materials that corrode, stain or fail easily.
- Modularity: There should be an easy way to maintain the product. This means avoiding areas where dirt might collect and ensuring easy access to all parts of the products. Maintenance can help to let products appear newer for a longer time, making them more attractive for reuse. Another part of modularity is the standardisation, compatibility and adaptability of the products. These aspects are required to ensure reuse. This means that a design can be timeless, so

creating an attractive design that is not influenced by fashion changes. Simplicity and functionality are factors that can help a product remain attractive for a longer time.

- Reliability: When is product is very reliable the owner will trust the product and often become emotionally attached. Even if the emotional connection is not there, in case a product is very reliable, the owner will probably prefer to use it instead of replacing it with a newer design, even when the product is not the latest, shiniest or most functional model.
- Cost: In case the product remains in good condition during the lifetime and is reliable, the value of the product can also remain at a good level. This means that, in the case of selling the product on the second-hand market, the owner of the product can get a good price for the product and will be more tempted to do so instead of discarding the product.

Repair:
Similar to reuse, repair also has a few properties for every key indicator that can tempt a user to repair a product instead of discarding it in case the product is not functioning as wished.

- Material choice: The chosen material should allow for repair since not all materials are easy to repair. An example of a material that is easy to repair is steel, which can be welded together again, whilst for example leather is hard to repair and may not have the same quality after the repair.
- Modularity: To enable repair, the first takeaway is to make a simple design that is easy to take apart. This means that the parts can be taken apart with standard tools or ideally without any tools, and that there are no parts glued. To be able to repair, standardized parts are key in order to be able to replace the broken parts instead of not being able to because the certain model or type of spare part is not manufactured anymore.
- Reliability: The product should still be reliable to use after the repair. This means that if the product is designed for repair this can be ensured but if the user needs to repair parts that have not been designed to be repaired, the quality of the product can not be ensured.
- Cost: For the choice of repair, the main decider will be the cost of the repair compared to the value of the product after the repair. If the product is designed for repair by use of the other key indicators, the cost of repair can be kept as low as possible and after the repair, the value of the product will be acceptable.

Another aspect that does not fall in any of the above categories but can be very helpful in enabling repair is to have good documentation on how to repair the product. This documentation should be understandable for every user. If the product is very complex and the strategy of design for repair by the user might be very hard or not possible, the supplier of the product should have a repair service to ensure good repair.

5.2.3. End of life: Refurbishment, Remanufacturing, Repurposing, Recycling and Recovery

For the steps of refurbishment, remanufacturing, repurposing, recycling and recovery, the design principles are similar except for the fact that for these R-values, a loop back to the manufacturing facility is required. Users are (often) not able to refurbish or remanufacture their products themselves. An example of creating such a feedback loop is the use of ”statiegeld” on plastic bottles and aluminium cans in The Netherlands. A concept that is used in many countries where you pay extra when buying a product and get back the extra money when you return the empty bottle or can to the seller, like a deposit.

To enable refurbishment and remanufacturing, the same design principles as for repair play a role; so creating a modular design design which can be easily disassembled in a non-destructive way and which is easy to maintain and clean.

For Recycling, the use of similar materials is very important so that materials can be recycled using the same method or process where there is no separation needed. Damage to the product in order to dismantle it is not important anymore but still, the product should enable for easy dismantling or disassembly.

Repurposing is mostly applicable to parts that are still in good condition but which will not come back in the same product. For this, compatibility is important to think about during the design phase.

The problem with recovery is that it is not a preferred method when it comes to the circular economy principles, especially not during the design phase where choices for different designs which are more circular can be made. If none of the other strategies is possible, recovery can happen and in that case, the material choice is the most important indicator. A lot of materials can be incinerated but hazardous materials need to go to landfill. This was already mentioned and explained in Figure 4.4.2.

5.3. Conclusion on key indicators

It can be concluded that during the design phase, (desired) lifespan and use frequency play an important factor in the choice of a design strategy. Products with a low utility rate can better be designed with a focus on recycling than on repair or repurposing, whilst products with high utility need a design focus on reuse, repair, refurbishment and/or remanufacturing. Material choice is a very important indicator in terms of determining the level of circularity of a product. The inflow of (reused/recycled) material determines half of the circularity of a product, whilst the outflow of materials defines the other half. The type of material determines what will happen with the product at the end of the product's lifetime when material recovery becomes important: recycling or recovery, or even landfill. But also during the lifetime, a material needs to be repairable if repair, refurbishment, remanufacturing or repurposing is desired. Cost plays an important role in the destiny of a product when it becomes obsolete for its current owner and should be kept as low as possible. Additionally, when designing for circularity, the retained value can be used to sell a product or parts of a product second-hand or to repair/remanufacturing/recycling facilities. Also, during design, modularity plays an important role and designers should focus on this to ensure that the circular economy principles can be followed by making it easier to dismantle a product. This also is important to achieve a high level of material recovery in case a product's lifetime ends. Lastly, reliability mostly plays a role during the product's lifetime, especially in the case of reuse, because reused, second-hand products must also be reliable for a second owner. All of these indicators play a role in the design of a circular product and will need to be taken into consideration during this phase. Lifetime and use frequency can be used to determine a design strategy. Modularity, material, cost and reliability are ways of achieving these design strategies. The aim should be to design a product that is as modular as possible, consists of as much reused material as possible, which can be maintained for the lowest cost possible and is as reliable as possible.

6 Application of the Circular Economy principles in Ship Design

In this section, the aim is to answer the fifth sub-question: *What is the impact of including circularity in the ship design approach?*. Now that the definition of circularity is clear, the circularity measurement method is chosen and the different design approaches have been reviewed, the next step of combining all this into a framework on how to design a vessel whilst applying the circular economy principles can be made. The framework should be standardised for every type of system on a vessel to be designed, no matter how big or small. How to combine systems engineering and circular economy principles to ensure circular ship design is explained in this chapter. The framework consists of six steps which will be elaborated upon one-by-one. An overview of the framework is shown in Figure 6.1.

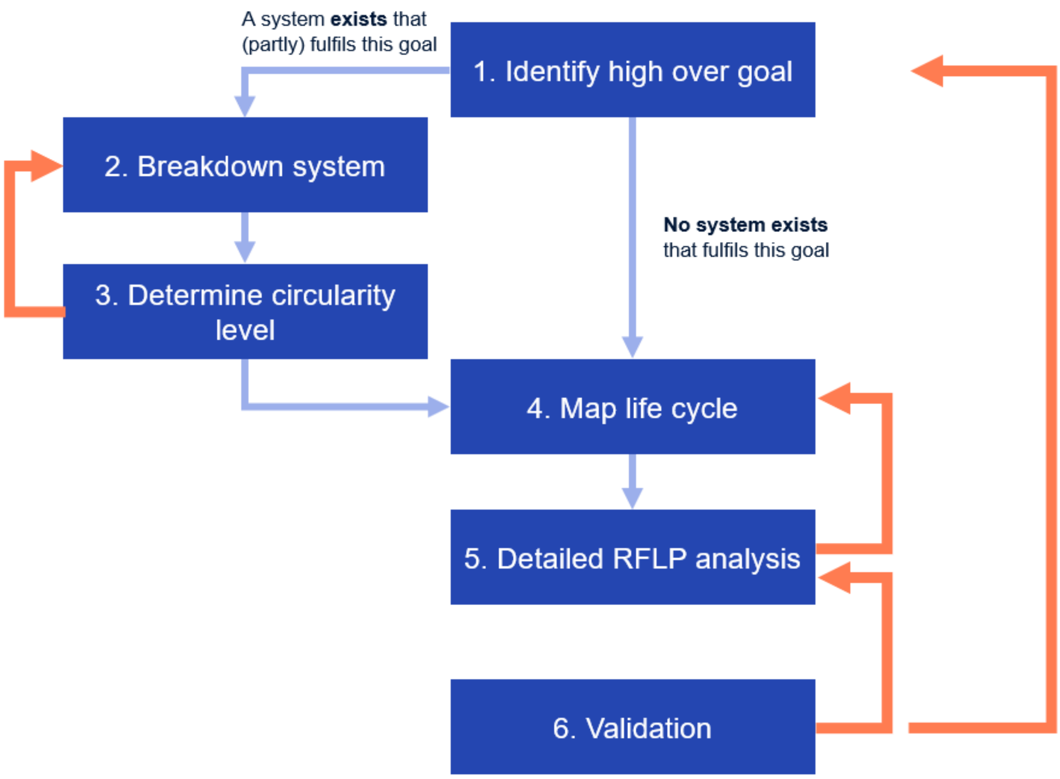


Figure 6.1: Visual of the framework for including the circular economy principles in the ship design approach

6.1. Step 1: Identify the overall goal

In systems engineering, the first step is a needs analysis. During the needs analysis, the goal is to show clearly and convincingly that there is a valid operational need for a new system or an update of an existing design. To do this, it needs to be assessed whether or not a system already exists that is meeting the needs or whether a (re)new(ed) system is required. In order to do so, the first step is to identify the overall goal or mission the system should fulfil (Hopman, 2021). In the case of designing for a system whilst taking circularity into account, there needs to be a general, operational goal and a circular goal. In this section, general goals and circular goals will be explained. It is important to note that this is a very high-over goal or mission, and more detailed descriptions will be defined in a later stadium of the design process.

6.1.1. General goal

When looking for a (re)new(ed) system, it is good to establish an overall mission that the system needs to fulfil. This way, it can be checked whether there is a system that already fulfils this mission or that there is a need for a new system. The general or main requirements are often dominated by three main parties; customers, production and regulations (B. Vink, Personal Communication, June 28, 2023). Where, in identifying the high-over mission, the customer often has the biggest say. Production and regulations often have more detailed requirements which will be explained in subsection 6.5.1. Next to that, an update of regulatory requirements can lead to a need for design renewals. Often, the overall goal is expressed in an operational requirement. An operational requirement is a requirement that refers to the mission and purpose of the system, whilst being very broad (Kossiakoff et al., 2011)ah. Another type of requirement is the functional requirement, which describes what the system should do. The operational and functional requirements can be used to see whether there is an existing system that fulfils these requirements. If this is the case, the system should also be checked for meeting the circular requirements which will be explained below. In case there is no system available meeting the operational and functional requirements, this is proof that there is a need for a new system that does meet these requirements. There are more types of requirements, influencing performance and physical aspects. These apply to the circular economy and will now be explained.

6.1.2. Circular goal

As said, besides operational and functional requirements, there can also be performance and physical requirements. Performance requirements refer to how well the system should perform its requirements and affect its environment (Kossiakoff et al., 2011). The physical requirements pertain to the qualities and features of the physical system, as well as the limitations imposed on the design due to physical constraints. Looking at the circular product indicators, requirements regarding lifetime and use frequency can be placed in the operational requirements. Physical indicators such as cost, modularity, material choice and reliability can be placed under physical requirements. These requirements are dependent on each other as explained in section 5.1. Not only do circular aspects have to be a part of the performance and physical requirements, but also general things such as the quality of the product can be performance and physical requirements. Ideally, the goal might be to have one hundred per cent circular systems, but this might not always be achievable. For the general circular requirements, it would be wise to specify this wish into different material streams. Examples of this would be to set a requirement that ninety per cent of the inflow of materials needs to be non-virgin, or at least ten per cent of the outflow of materials should be used in remanufacturing.

6.1.3. Results after step 1

After completing step 1, the user of the framework should have set a clear goal/mission for the system that is going to be (re)designed, including a clear circular goal. Based on the set requirements there are three options;

1. A system exists that fulfils the high over requirements.
2. A system exists that fulfils the operational requirements but not the circularity requirements.
3. No system at all exists that fulfils neither the operational nor the circular requirements.

In case a system already exists that fulfils all requirements, no need exists to design a (re)new(ed) system. In case a system exists that fulfils the operational requirements but not the circularity requirements, step 2 should be carried out. In case no system at all exists that can fulfil any requirements, steps two and three of the framework can be skipped and step four should be carried out.

6.2. Step 2: Identify and breakdown system, sub-systems, components, sub-components and parts

On board vessels, many systems are present fulfilling many functions and requirements. Once the overall goal has been defined, the system that already exists (partly) fulfilling this high-over goal needs to be assessed. This can be done by breaking down the large system into smaller pieces and having a look at the functions and interactions between these systems by use of architectures. Therefore, in this section the definition of all system levels will be given, the system boundaries will be explained, a way of visualising the connection between the different system levels through architectures will be elaborated upon and lastly, information will be given on how to put the theory into practice.

6.2.1. Definition of System levels

Before developing a (re)new(ed) system, it is important to identify and define a system. According to Kossiakoff et al. (2011), the term "system" should only be used "for entities that 1) possess the properties of an engineered system, and 2) perform a significant useful service only with the aid of human operators and standard infrastructures" (Kossiakoff et al., 2011). As already explained and shown in subsection 4.1.4, a system follows a hierarchy structure where a system consists of a number of sub-systems, which in themselves are composed of components, which are composed of sub-components which are in the end composed of parts. A sub-system is a major part of a system that performs a closely related subset of the overall system function. This can mean that a sub-system in itself might be quite complex and has the properties of a system, but cannot perform a useful function in the absence of other sub-systems. The term components is used to refer to the middle level of system elements. Components are built of sub-components which perform elementary functions and are composed of several parts. Parts are the lowest level of the system hierarchy and these are elements that perform no significant function except in combination with other parts. How far a system can be broken down for analysis is very dependent on the information provided; if no information is there on the structure of the system because, for example, the system is designed by a separate company, this is hard to break down further. In this case, the supplier of the system needs to be contacted to get more information or the assessment should be done until this level of detail. This is a choice during the definition of the system. The selection of what to select as the system needs to be based on the goal the system should fulfil according to step one. This decision will also determine the level of detail that can be achieved in the identification of the system levels.

6.2.2. System Boundaries

In order to identify the environment in which a new system operates, the system's boundaries need to be identified, by defining what is inside the system, and what is outside. Several criteria can be used to help determine whether an entity is part of a system or not; Development control, operational control, functional control and unity of purpose. For every criterion, questions can be asked such as; "Does the system developer have control over the entity's development?" and "In the functional definition of the system, is the systems engineer "allowed" to allocate functions to the entity?" (Kossiakoff et al., 2011).

An important, basic choice in the early stages is to determine whether human users or operators of a system are considered to be part of the system or are seen as external entities. This is because in case the operators are external to the system, the engineer will need to focus on the operator interface.

Entities that are not part of the system, will still interact with it. A method that can be used to display the interactions with systems and external entities is the context diagram. A generic diagram is shown in Figure 6.2. The diagram has three pillars: 1) The external entities, constituting all entities in which the system will interact. 2) Interactions, representing the interactions between external entities and the system in the form of arrows. 3) The system, typically an oval, circle or rectangle in the middle with the name of the system within. The arrowheads show the direction of an interaction. To identify what is being passed across the interface, each arrow is labelled. According to Kossiakoff et al. (2011), five categories can be distinguished for the interactions: Data, signals, materials, energy and activities.

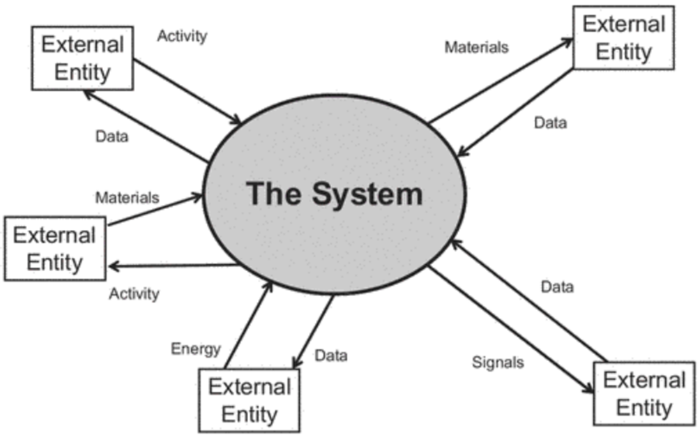


Figure 6.2: Context diagram (Kossiakoff et al., 2011)

The limits of the system can thus be physical but it is often hard to set the boundaries this strict because there are always external entities interacting with the system. It is the choice of the person analysing the system where the limit of the system is, based on the goal the system must fulfil as defined in step one. Every part of an object that fulfils this goal can be seen as part of the system, together with all the parts that are connected to these functional parts.

6.2.3. Functional, Logical and Physical architectures

To get a better sense of the structure of the system, the interactions on multiple levels of a system can be evaluated by the use of architectures. Architectures help to capture the relationship between the different elements of a system. There are functional, logical and physical architectures. The visualisation of this is shown in Figure 6.3.

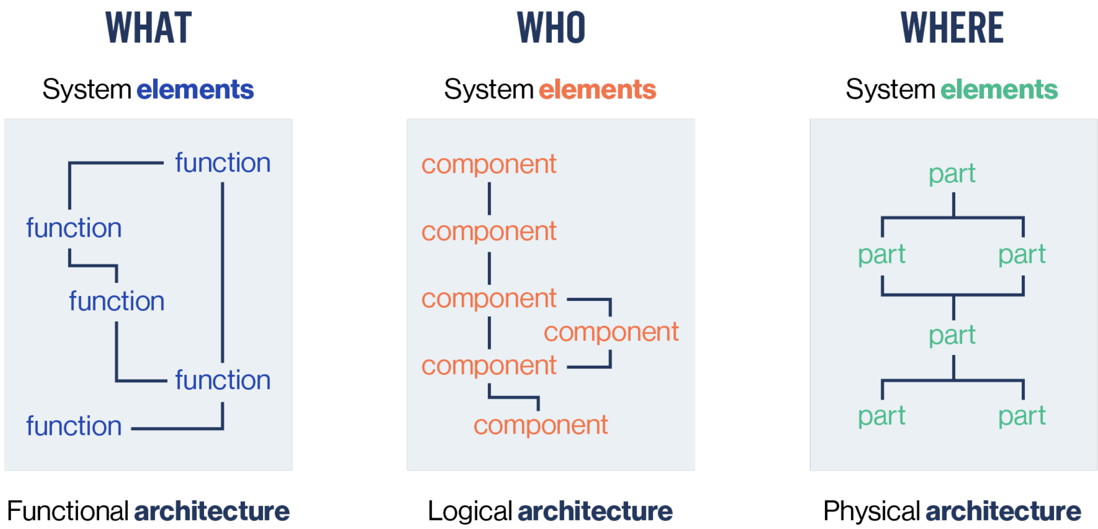


Figure 6.3: Visualisation of a functional, logical and physical architecture, based on The Mathworks (2020)

The first architecture, the functional architecture, shows the functional relationship of different elements. A function is a task or activity that must be performed to achieve a desired outcome or as a transformation of inputs to outputs (Hopman, 2021). An example of a function is shown in Figure 6.4. The functional architecture can also be called a Functional Flow Block diagram (FFBD). In the FFBD, the different function blocks are connected by unidirectional arrows that show the order of function execution (McInnes et al., 2011). Often the FFBDs are drawn from left to right and from top to bottom. The FFBDs can also be layered in a hierarchy of diagrams that progressively provide more detailed descriptions of individual systems. By breaking down the system by use of an FFBD and visualising the interrelations, a designer can better understand the system's overall behaviour and use it to identify potential issues or improvements, and thus find a need for a (re)new(ed) system.

Similar to function mapping, the logical and physical architecture can be mapped out. The logical architecture consists of components linked to each other, to see whether these components are grouped in a "logical" way. Components can be implemented in software or in a physical way, where the overview of the physical connections between parts is the physical architecture.

Figure 6.4: Visual of the meaning of a function, based on The Mathworks (2020)

6.2.4. Putting theory to practice

After all these theoretical boundaries and frameworks on how to identify the system, practice might prove to be different. In reality, one needs to work with the information available. This information could be retrieved from drawings of systems, material lists or other documentation. The level of detail per system might differ since some systems might be designed and built by the company performing the analysis whilst others might be designed and built by suppliers. This means that contact with suppliers plays a key role, but they might also use suppliers for certain components or parts on which they do not have sufficient information to map a system into detail. In the selection of systems that will be analysed, it can be profitable for the company performing the analysis to select the systems that they have control over, because in that case, most likely more information is available. Additionally, if changes are suggested in the next steps for the system, these changes can be made by the company themselves instead of having to instruct and demand suppliers to make a change. Next to that, the circularity of the systems is measured based on weight, resulting in the heaviest components or parts having the biggest influence on the total circularity level of a system. Thus selecting a heavy system when having the choice between multiple systems to assess is an effective way to increase the circularity level.

6.2.5. Results after step 2

After completing this step, a system that currently fulfils the overall goal has been identified and the boundaries of the system are known. Next to that, the system has been broken down into sub-systems, components and parts. The connections between the different levels of the system have been visualised by the use of functional, logical and physical architectures.

6.3. Step 3: Determine the current level of circularity of existing design

Before redesigning an existing system that already meets the operational requirements but does not meet the circular requirements, the current level of circularity needs to be determined to have a baseline. With this baseline the improvement in terms of circularity after the redesign can be measured. This baseline can also be used to show the need for redesign, when a system is not circular enough, according to the requirements. To make the baseline, first, the information that is required for the MCI will be explained. Then, ways to acquire this information will be set out and finally, a need analysis will be performed.

6.3.1. Material Circularity Indicator

As explained in Equation 3.2.1, the selected method to measure the circularity of a system is the MCI. Before the measurement of the system starts, it is very important to determine the scope of the measurement; which parts of the system will be included in the assessment and which parts will be left out. It is therefore very important to have completed step 2 so it is known what options there are to assess. Some parts that were identified in step 2 might be taken out of the assessment because the assessment of all little parts of a system might take up too much time, not being worth the effort. For example for the circularity assessment of Damen's RSD-E Tug Sparky, only systems/parts above 400 kg were taken into consideration (Collier, 2023). The level of detail therefore depends on the size of the identified system. When the system to be reviewed is a whole vessel, there is less need for measuring the circularity of every bolt and nut, but a high-over measurement is also representative. Whilst if the identified system is a laptop, the level of detail becomes way more important and also the little parts have to be assessed. After the level of detail has been determined, the MCI can be used to measure the current level of circularity.

During the assessment of a system on its current level of circularity, material choice, modularity, reliability and cost play an important role. Looking at a circular system, for the inflow as much previously used material should be included. To get information on this, good contact with suppliers is key. For the outflow, the material should allow for a certain level of circularity, the modularity should be high enough to allow for easy dismantling and the cost of each R-level should not be higher than a lower level. Designing in such a way that the product can be fully circular is the goal here since there is a lack of control over the rest of the lifetime once the system is sold to a new owner. The overview of the inputs, flows and outputs of the MCI in the form of symbols is shown in Figure 6.5.

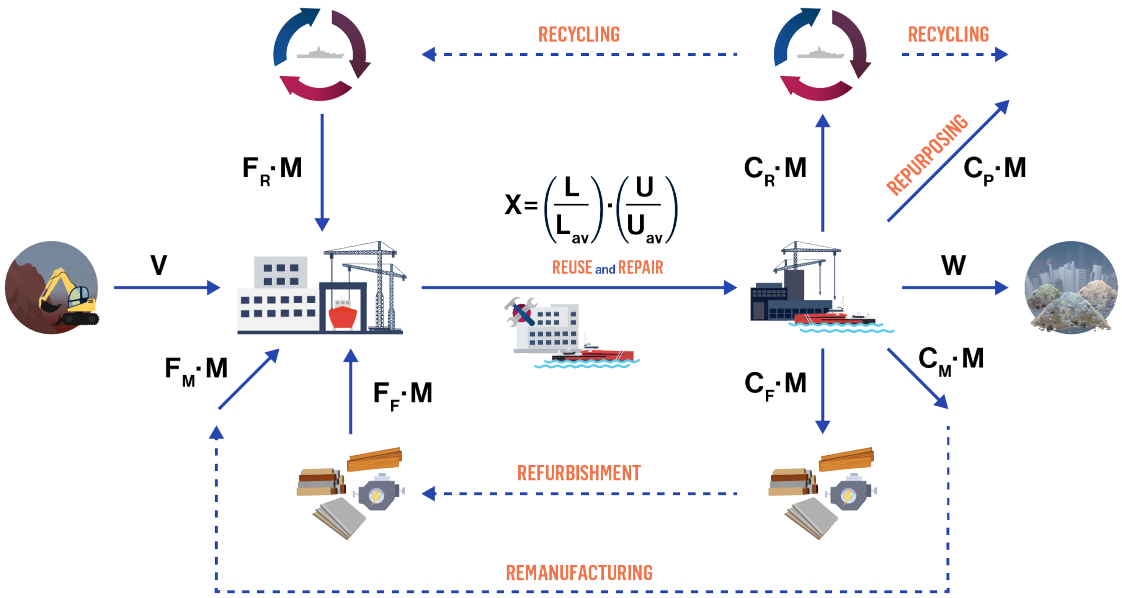


Figure 6.5: Overview of flows in the Material Circularity Indicator

For every input of the MCI calculation, different R-values play a role, connected to different key indicators as presented in section 5.1. For the input, the principles of refuse, reduce and rethink are important. During the lifetime the principles of Reuse and Repair are needed to ensure an as long as possible lifetime. During the final stages of the product in its current state, the principles of Refurbishment, Remanufacturing, Repurposing, Recycling and Recovery are important.

For every input, multiple questions can be asked in order to determine the contribution of the input. For the inflow of materials, the key indicator of material choice is the most important. The most important question here is; have non-virgin materials been used, and are these materials reused or recycled materials? The inflow is often controlled by designers and suppliers. Therefore this is where the biggest influence of this research can be. A very important aspect here is good contact with suppliers to get information about used materials, but also to ensure the reuse of non-virgin materials in the future.

The steps taken regarding circularity during the product's lifetime depend a lot on multiple key indicators. The choice for reuse depends on the reliability of the product; is the product reliable enough to reuse? For repair, all indicators play a role; Are the cost of repair lower than the cost of other value-retaining steps? Is there a high retained value after repair? Is the material suitable for repair? Is the product design modular to enable repair? Will the product still be reliable after repair? The same questions hold for refurbishment and remanufacturing.

At the end of life, once again almost all key indicators play a role. Example questions for recycling are; Is the cost of recycling lower than the cost of disposal? Does the recycled material have any retained value? Is the product built modularly so it can be dismantled into different materials? Does the material choice allow for recycling? The same questions hold for refurbishment, remanufacturing, repurposing and recovery. Even though recovery is not preferred, it is still better than disposing of the material in a landfill. Also for recovery, these indicators are important, since not all material can be incinerated. The overview of the MCI connected to the 10R framework is shown in Figure 6.6

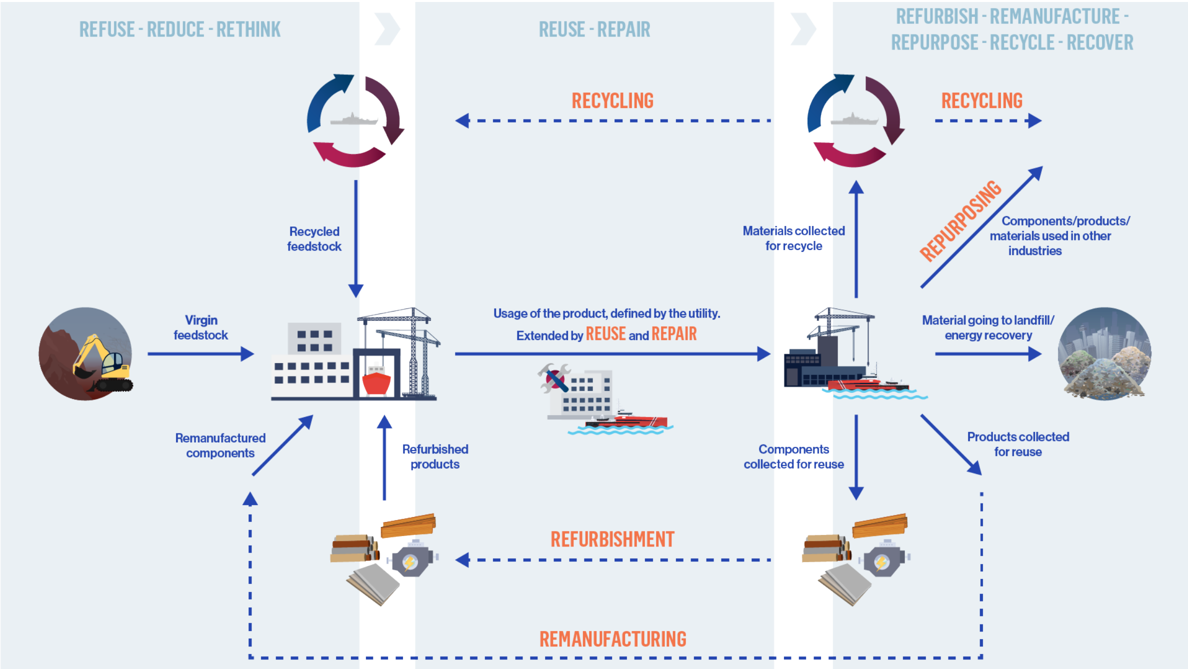


Figure 6.6: Overview of the 10R framework in combination with the MCI .

6.3.2. Acquiring information for the MCI

Once again, the theory might be clear and sound straightforward, but in practice gathering information to be able to fill in the MCI is more challenging. The selected system can either be designed by the company assessing it, or it can be designed and delivered by a supplier. This can be a big difference in the availability of information. Now, for every topic on which information needs to be gathered, input will be given on how to acquire this information.

Weight

First of all, the weights need to be known. To assess the same level of detail as the system has been broken down in step two, the weight of every part as identified in this step needs to be known. This information could be gathered by the use of in-house information or supplier information. When a system has been designed in-house, most likely there is information available in terms of a product sheet or other drawings that have information on the weights of different components and parts. In case the system comes from a supplier they might be able to provide product sheets or other sources that give information about the weights. Another source that might provide useful information is the weight calculation of the vessel. In the weight calculation, the weight of a complete vessel is calculated by listing the weight of different sub-systems. At Damen Shipyards this weight calculation is ordered per system code. The system codes are specific for Damen Shipyards and divide the vessel into sections such as code 100 for the hull and outfitting, or code 200 for the main machinery. In every big code, there are further differentiations for the sub-systems such as code 151 for the fenders or code 712 for all walls onboard. However, in a weight calculation, the level of detail does not go as far as specifying every bolt and nut. This means that there is a lack of information that needs to be overcome. In this case, the mass M in the MCI will be the mass of the whole system or sub-system and the percentages of F_M, F_F and F_R need to be estimated.

Recycling, Refurbishment, Remanufacturing and repurposing percentages

To identify the percentages of recycled, refurbished or remanufactured in the inflow of materials, the most important factor is the material choice. Information about the material can often be found on the bill of material, or on the material list of a vessel. However, often only the type of material is listed here, whilst the interest for the inflow of material is in the origin of the material. Therefore contact with the supplier of the material is key to acquiring this information. Because even though a company such as Damen might design the hull of a vessel, the steel to build the hull will probably be delivered by an independent supplier.

Suppliers play a key important role in gathering information about the system to be able to perform the MCI calculation. In case the suppliers are not able to provide the required information, industry averages can be used. Industry averages regarding the inflow of materials can be found in a material database. An example of such a database is Ansys Granta Edupack. The MCI has been developed by Ansys Granta Edupack in collaboration with the Ellen MacArthur Foundation. Even though the use of industry averages is a better alternative than assuming only virgin inflow when suppliers are not able to provide the information that is required to fill in the MCI calculation, the use of industry averages will not always result in a precise circularity percentage. An example of this is the recycled content in steel. The industry average that Ansys Granta Edupack provides is a range between 36 and 39 per cent. However, there are two methods to produce steel; The blast furnace and the electric arc furnace process. About 70% of the world's steel is manufactured by use of the blast furnace technology and the other 30% is produced by the electric arc furnace process (American Iron and Steel Institute, 2023). An important difference between the two processes is the amount of scrap steel that is used to produce new steel; approximately 5% of the input for the blast surface process consists of scrap whilst for the electric arc furnace method this is 70%. This is an example where the industry average will never be correct since the actual percentage of recycled content depends strongly on the production process that was used.

For the outflow of materials, multiple factors play a role. Material choice, modularity and cost play an important role. Also, the business model that comes with the system can have an influence on the outflow of materials at the end of life. If the system is still in operation, the exact circularity cannot be calculated yet and only the potential can be explored. This potential can be discovered by asking questions about the material, modularity and cost as explained above. Material potentials can be explored by use of industry averages. Unfortunately, there is no standard database that has information on the reuse or recycling potential of different material types.

Questions to ask suppliers

To get the right information from suppliers to fill in the MCI calculation, multiple questions need to be asked. They will be listed below. In case a supplier does not have any information on a topic yet, asking the question might give the incentive for the supplier to start thinking about circularity. If enough clients start asking questions and are demanding more circular products, a supplier will also have to make the change in the right direction.

- Inflow: Is there information available on the origin of the materials? Are there any materials present in the system that were remanufactured, refurbished or recycled?
- Lifetime: What is the lifetime of the system? Is there any information on the lifetime of similar systems? What is the use frequency of the system? Is there any information on the use frequency of similar systems?
- Outflow: Does the business model allow for taking back the used product? Can used components or parts be handed in at the supplier to enable remanufacturing or refurbishment?

All the information needed to fill in the MCI calculation can be retrieved with these questions but it depends on the information provided by the supplier to what level of detail the calculation can be performed.

6.3.3. Results after step 3

After completing step 3, the goal is to have a circularity percentage for the system that is being assessed. This circularity percentage can preferably be split up all the way to part-level but if the information to perform the calculation was not that extensive then a global circularity percentage is also acceptable.

Based on this circularity percentage, the parts and components that influence the circularity percentage in a negative way can be identified.

After completing steps one to three, the need for a new system has to be validated. Is there no system existing yet that fulfils the overall mission and physical (circularity) requirements? Then a need exists for a (re)new(ed) system. The system should have a valid operational need, but should also be technically and economically feasible. Therefore, time and money also play a role during the need for verification. As explained in subsection 4.1.4, the first three circularity values of Refuse, Reduce and Redesign play a very important role here. In case the need for a new or updated system is not clear, it is important to refuse this in order to prevent material use. It is a good moment for stakeholders to look at their consumption behaviour and in this stage decide to design or refuse to design a new system. Also, during this stage, upgrading a system should be prioritised over designing a new system. This follows the CE principle of reduce by using as little (new) material as possible. Due to the fact that a circularity assessment was performed, the designers can see where the problems occur regarding the application of the circular economy principles of an existing system fulfilling the overall mission. This way the circularity pillar of redesign is also addressed. In case it can be concluded that a valid need exists for a (re)new(ed) system and it is technically and economically feasible, step 4 can be executed.

6.4. Step 4: Map the system life cycle and associated stakeholders

After determining that a valid need exists for a system, the life cycle of the system has to be mapped to identify stakeholders and determine the operating environments. This way, the stakeholders that will set the requirements for Step 5 are identified. The mapping can either be done by assessing a current system that was almost meeting the requirements but requires an update, or by mapping a completely new system. Even though the detailed description is not known yet, by use of the overall mission the operational area can be identified, as can the stakeholders. In this section, first, the steps in the life cycle of a system will be elaborated upon after which the stakeholders will be identified.

6.4.1. Steps in the life cycle

First, the steps in the life cycle of the system need to be assessed. Another term for the visualised steps in the life cycle of the system is a value chain. The value chain encompasses all the necessary steps involved in taking a product or service from its initial idea stage through the various stages of production (including physical transformation and the involvement of different producer services), delivery to end consumers, and ultimate disposal after use (Kaplinsky and Morris, 2000).

For example, for a ship, life cycle steps such as engineering, manufacturing, commissioning, operation and decommissioning play a role. These are very general steps and during the operational phase even a further breakdown can be made regarding the operational area; will the vessel sail in Arctic waters or in a tropical area? An example of the ”standard” steps during the lifetime of a vessel is visualised in Figure 6.7. All these steps of the life cycle have to be mapped in order to get an idea of the stakeholders that play a role in the lifetime of the vessel because all these stakeholders might have requirements that have to be considered during the design phase. Even though the same steps from design to operation to decommissioning exist for many systems, the exact environment of these life cycle steps can differ enormously. Operating areas can be identified alongside conditions in which the main mission has to be accomplished (Hopman, 2021).
To help guide a designer in mapping the life cycle, Kossiakoff et al. (2011) suggests mapping or modelling at least the following circumstances:

1. ”storage of the system and/or its components,
2. transportation of the system to its operational site,
3. assembly and readying the system for operation,
4. extended deployment in the field,
5. operation of the system,
6. routine and emergency maintenance,
7. system modification and upgrading, and
8. system disposition.”

The model of the phases must be detailed to such a level that any interactions between the system and its environment that will affect its design are precise.

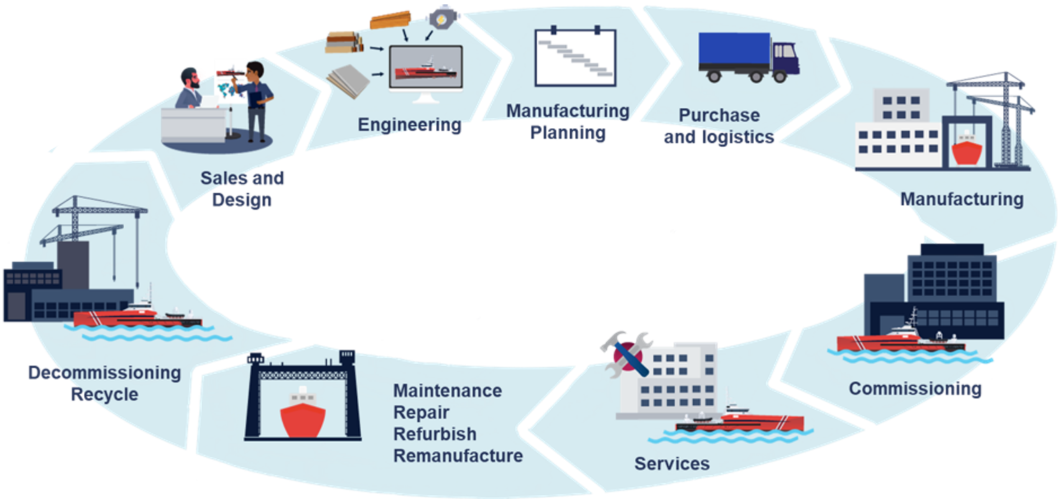


Figure 6.7: Standard steps in the life cycle of a ship (Damen Shipyards, 2023b)

6.4.2. Stakeholder analysis

With every step in the life cycle of the system, one or multiple stakeholders can be identified. This is important because stakeholders have needs and the purpose of design is to satisfy these needs. For the mapping of the stakeholders, not every stakeholder is of equal importance. Additionally, often the needs that different stakeholders have are in conflict. Stakeholders can be divided into the direct beneficiary and several indirect beneficiaries (Erikstad, 2018). The direct beneficiary is the direct customer or contract partner of the new design. This is often the owner or operator of the system to be designed. Other very common stakeholders in the maritime sector are charterers, suppliers, design companies, regulators, governments, etc. An overview of the most common stakeholders with regards to a general vessel that needs to be designed was already given in section 2.5. However, for a specific system that needs to be designed different stakeholders might play a role or the level of importance of the stakeholders can differ. By use of looking at all the life cycle stages, the associated stakeholders can be identified and their level of importance can be determined. Prioritisation could be done based on the level of influence and impact but also the urgency of their requirements. Next to that, money will play a role; the one that pays often has the biggest say but also needs to comply with regulations.

Stakeholders and circularity

When looking at stakeholders and their needs with regard to circularity, often an outside incentive is needed. Here, the regulations as explained in section 2.2 can be the main driver. For every stakeholder, a different regulation will be of the appliance. The main question for the circularity requirements is; Who will take responsibility for asking for a circular product? A standard that might give a push in the right direction is the obligation for companies to bring out a Corporate Sustainability Report (CSR). The goal of the CSR is to mobilise the private sector to contribute to the EU's plan to transition to a fully sustainable and resource-efficient economic and financial system. Currently, companies have to publish information on topics such as environmental matters, respect for human rights, diversity on company boards, etc (European Commission, 2023a). As of 2024, circularity will also be a part of the topics companies have to report on. How to report on this, will be based on the ESRS as drafted by the EFRAG (Coalition circular accounting, 2023). When all companies do this, and the CSR is implemented in the right way, financiers, customers and policymakers will be able to compare and contrast businesses based on their commitment to the circular economy. This means that customers will be able to make choices between suppliers based on material extraction of waste generation, instead of just quality and price (Coalition circular accounting, 2023). Additionally, investors will have the opportunity to focus their investments on enterprises that strive to separate their financial achievements from reliance on finite resources. This will be a good incentive for companies that are not scoring well in terms of resource use, to come up with a strategy and goals on how to achieve higher levels of circularity, pushing towards circularity for all stakeholders in the lifetime of a system.

A strategy to reach more circularity within companies is to set company-wide goals that are measured by indicators; Key Performance Indicators (KPIs) (Coalition circular accounting, 2023). These indicators can help stakeholders in guiding them in defining requirements they have with regard to circularity. An example of a KPI can be a certain percentage of systems that are sold in the past 30 years that are still active in the field (reuse). Or the goal to reach a certain percentage for the recycling rate of used products. Setting these KPIs as a company is important in order to set a clear goal for the future and be able to steer on that goal (Parmenter, 2015). In case a company has public goals with regards to circularity, suppliers that can deliver products that help a company reach this goal can also use the goals as a selling point for their product; attracting more and more sustainable suppliers. In case a company does not have KPIs on circularity yet, it is recommended to first draft these before setting needs for a specific system.

To develop circular requirements, it is important to think from a life cycle perspective. It might be hard to get all stakeholders to have this same vision since many stakeholders only play a (financial) role during very small parts of the life cycle. Therefore, it is very important to prioritise the needs of stakeholders and the designer might need to have a negotiating role in this.

6.4.3. Results after step 4

Once step 4 has been completed, the result should be a mapping of the life cycle of a system that fulfils the overall goal and with every step of the life cycle the stakeholders should have been identified. Preferably, different life cycles have been made for the current situation, in a linear economy, and the preferred life cycle, that shows a circular flow. This way the differences can be identified and focus points in the new design are known.

6.5. Step 5: (Re)design the system by use of the RFLP method, applying circularity principles

As explained before in subsection 4.1.4, one of the applications of the systems engineering approach is the RFLP method. The technique uses requirements to define functions, which are connected by logic and then put into a physical form. It is essential for every step that the level of detail of the previous step is sufficient to make the next step. How the stakeholder needs flow into functions, functions into components and components into physical parts, is shown in Figure 6.8. The requirements always play a role and influence every stage of the design process.

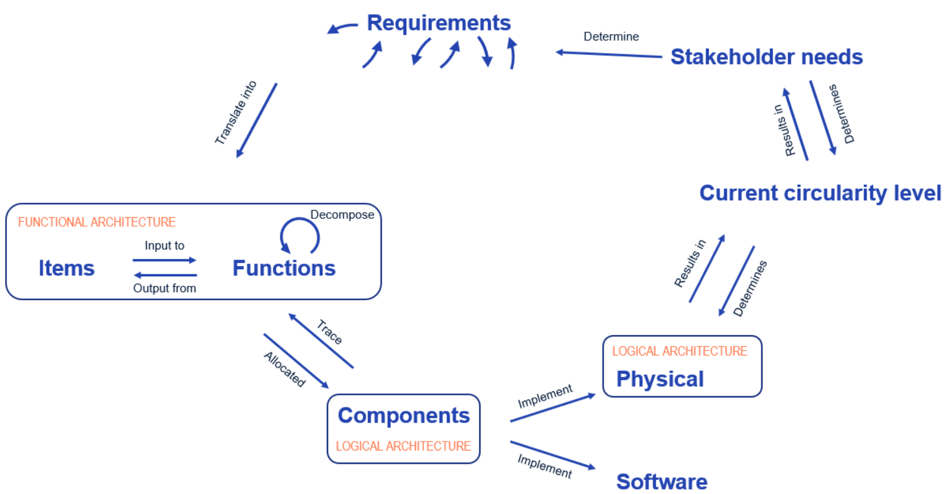


Figure 6.8: Overview of the RFLP method based on The Mathworks (2020)

However, the process of systems engineering is not linear and needs to be repeated many times until a sufficient level of detail is reached and a system has been developed which meets all the requirements. This process is shown in Figure 6.9. The steps of RFLP are listed in a linear order, but in practice, the steps need to be repeated over and over and there should be a constant loop back between all elements to check if the functions match the requirements if the requirements are represented in the physical system, etc. Requirements can change and might need further detail, as goes for the other steps. For the sake of readability, the RFLP process will be written down in the order of requirements, functions, logical and physical but this will as said be a looping process in practice.

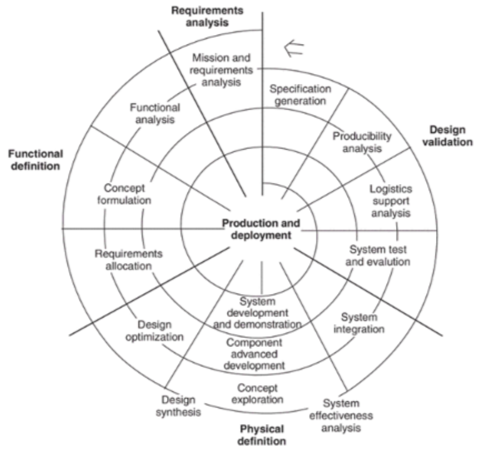


Figure 6.9: Spiral model of the system life cycle development (Kossiakoff et al., 2011)

6.5.1. Requirements

The first step of creating a (re)new(ed) system is to set up the requirements the system has to comply with. These requirements are determined by the stakeholders as identified in step four. Every stakeholder has their own needs and interests. To meet the needs of all stakeholders, it is important to gather all needs and rank them in terms of importance. During the design phase of systems for maritime applications, there are often three main stakeholders: The regulation societies, the production facilities and the customer buying the system. The customer has a need for a system and wishes for it to be able to do certain activities. For the execution of these activities class societies have certain rules that a system has to comply with. Additionally, the production facility needs to be able to produce a system that can fulfil these requirements, so they will have requirements regarding for example the availability of materials.

Setting requirements

As explained in section 6.1, there are different types of requirements; operational, functional, performance and physical requirements. Often, the performance requirements are an interpretation of the operational requirements (Kossiakoff et al., 2011). The idea is to start off with collecting and defining the operational requirements; what is the mission and purpose of the system? Examples of defining operational requirements for a vessel could be to identify what kind of cargo it should transport or in which region it should sail. From the operational requirements, the performance requirements can be derived; in case it needs to transport cargo, what is the required sailing speed? what areas should be present on board? Every time operational requirements are defined, these should be checked whether they comply with the operational requirements.

To check requirements, a requirements analysis can be executed. Requirements need to have certain characteristics; they should for example be feasible and verifiable. A test can be carried out to see whether or not a requirement is valid. Many tests have been developed by numerous organisations, but the test presented here is the test proposed by Kossiakoff et al. (2011) that sets a baseline.

1. ”Is the requirement traceable to a user need or operational requirement?
2. Is the requirement redundant with any other requirement?
3. Is the requirement consistent with other requirements? (Requirements should not contradict each other or force the engineer to an infeasible solution.)
4. Is the requirement unambiguous and not subject to interpretation?
5. Is the requirement technologically feasible?
6. Is the requirement affordable?
7. Is the requirement verifiable?”

In case any of the questions can be answered with ”no”, the requirement needs to be revised, or possibly excluded. This test is for individual requirements, but a test should also be carried out to see if all requirements together are sufficient. According to Kossiakoff et al. (2011), this test can be done by answering the following three questions:

1. ”Does the set of requirements cover all of the user needs and operational requirements?

2. Is the set of requirements feasible in terms of cost, schedule, and technology?
3. Can the set of requirements be verified as a whole?"

Identifying Circular Requirements

In addition to the currently common practice of operational and performance requirements defining, circular requirements should be defined. These can be seen as operational, performance and physical requirements. For every type of requirement, different key indicators as identified in section 5.1 play a role. Regarding operational requirements, key indicators such as lifetime, use frequency and reliability can be used as identifiers. These indicators are often requirements which are defined by the customer of the system. In terms of circularity, the desired lifetime should be as long as possible, and use frequency and reliability as high as possible. However, this of course depends on the needs of the stakeholders and they often need external incentives such as regulations to come to these desires. Once the operational requirements regarding lifetime and use frequency have been determined, the design strategy can be identified by the use of the principles explained in subsection 5.2.1. With this method, based on the required utility level the design strategy that should be prioritised can be chosen. The required circular design method can be seen as a performance requirement. Based on this performance requirement, physical requirements can be drafted in terms of cost, material choice and modularity. For the inflow of materials, a circular requirement will always be to use as much non-virgin material as possible. A requirement will of course also be to have as much circular outflow as possible, but this can be done in various ways and therefore the design strategy is important to determine.

As an example: The operational requirement can be that the lifetime of the system should be at least 20 years. Based on this operational requirement, the performance requirement of design for reuse can be identified. So a performance requirement is that the system should be reused for as long as possible. Based on this, physical requirements can be identified; for example, the material to be used must be durable and of good quality.

Visualising Requirements

Often, requirements are put into a requirement breakdown structure which is divided into multiple categories. Examples of high-over categories for requirements in ship design are speed, fuel management, comfort, etc. However, these differ a lot per vessel type and the purpose of the vessel. The requirements breakdown shows a hierarchical tree-like structure as shown in Figure 6.10. This way, the requirements for the high-over system can be mapped but also the requirements for sub-systems and even components can be shown this way and in a hierarchical way. This structure can also be used for the requirements analysis to see whether the whole set of requirements is sufficient to cover the needs of all stakeholders.

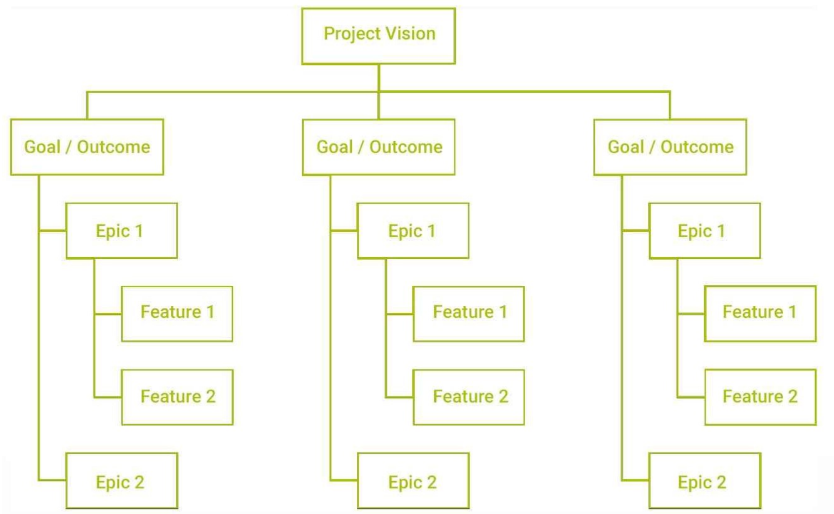


Figure 6.10: Example of a requirement breakdown structure (Reqtest, 2020)

6.5.2. Functions

Once the requirements have been identified, the next step in defining the system is to define the functions. A function often consists of a verb and a noun/object (The Mathworks, 2020) and the in and outflow of a function is information, energy and/or material (Hopman, 2021). So it is a task or activity that must be performed to achieve a desired outcome. Functions are mostly the result of operational requirements. The function definition is an analysis of the functional capabilities that the system should have in order to perform the desired operational actions. To get from requirements to functions, there is no deductive approach but the process is more inductive. Based on logic and experience, requirements can be translated into functions. Sometimes requirements, especially operational requirements, can also be a function; for example, laying and installing cables can be an operational requirement of a cable-laying vessel, but it is also a function. According to Kossiakoff et al. (2011), there is no direct method of translating requirements into functions that are necessary and sufficient to fulfil those requirements. Designers must rely on experience-based heuristics, and to a large extent, on a trial-and-error approach.

Circular functions

Because functions describe an action that needs to be performed, circularity is hard to capture in terms of functions. This means, that the influence of the circular requirements is minimised in this step of the systems engineering because the operational requirements, such as ”lift objects and materials” say nothing about circularity. The idea of a function as shown earlier in Figure 6.4 is to have an input before and an output after a function. However, systems that are more circular might have an influence on the performance of the function; a reused engine might have a bit of a lower performance than a brand-new engine (R. J. Joensuu, 2023). This means that stakeholders might have to make trade-offs between circularity and performance. On the other hand, it is a misconception that circular materials always have lower performance or functionality than raw materials, recycled steel for example has the same properties as steel made from raw materials (American Iron and Steel Institute, 2020).

6.5.3. Logical

Once the requirements and functions have become clear, logic comes into place to see where logical connections can be made. However, this is also a step that needs feedback, because in the next step, the physical components will be defined based on requirements and functions. When multiple components can be combined into a logical module, this step needs to be repeated to enable that.

Applying logic to the design is something that comes back in the key indicator of modularity; if systems or parts are connected in a certain way, they will be or not be suitable for repair, remanufacturing, recycling, etc. This means that in the phase where the components, which then again consist of parts, are identified, these components need to be connected in a modular way that allows for these actions. Modularity can also be seen as a way of standardisation. Standardisation is also a way to ensure circularity since a standardised process is optimised and thus has minimal waste during the process. Standardisation was long thought of as to not be an option in shipbuilding, but for Damen Shipyards it is the business model. Therefore logic comes into place in making choices on what components can be standardised and what has to remain customised for every system. Next to modularity, the cost can also play a role in identifying connections during the logical analysis.

6.5.4. Physical

By use of the identified requirements, functions and logical connections, physical elements for the system can be selected. There is no clear step-by-step process on how to do this, but it is an iterative process where the level of detail gets more and more clear with every step. In Figure 6.11 an example of a method is shown on how to get from a function to a specific, physical element. Availability on the market needs to be explored to find physical solutions that match the requirements, functions and logical structure that have been defined in the previous steps. The process for this will be elaborated upon in the section about the product specifications.

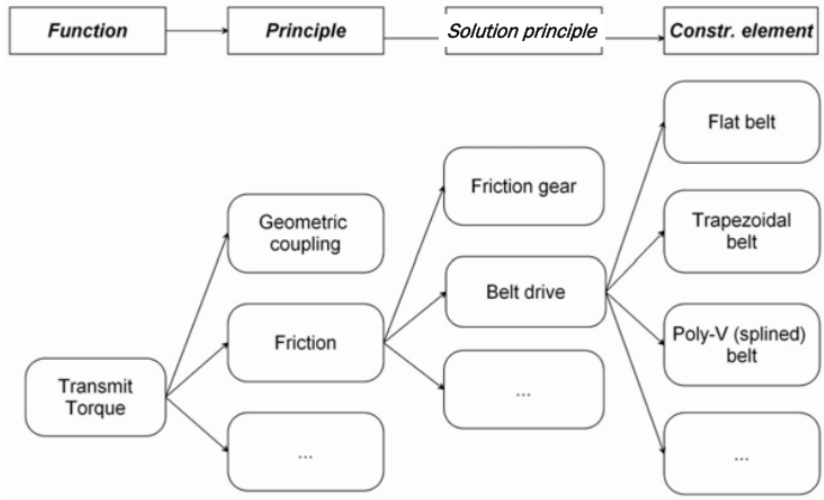


Figure 6.11: From Function to Physical solution mapping (Pahl et al., 2007)

A way to explore the options and make a decision between different possibilities is a morphological chart as presented by Zwicky (1969). The goal of the morphological chart is to provide a structured approach to concept generation to widen the area of search for solutions to a defined design problem (University of Cambridge, 2016). A product's necessary functionalities are captured visually to explore alternative means and combinations of achieving that functionality. For each product function, there might be numerous solutions. The process starts with listing the product functions at an appropriate level of generalisation. For this, the functions determined in subsection 6.5.2 can be used. After this, the "means" or possible solutions by which the functions might be achieved have to be listed. This can be on a material level but also shape or colour-wise. To visualise this, the functions are listed in the first column, and the possible solutions are listed in the rows. An example of this visualisation of shown in Figure 6.12.

	Sub-solution 1	Sub-solution 2	Sub-solution 3	Sub-solution 4	Sub-solution 5	Sub-solution 6
Sub-function 1						
Sub-function 2						
Sub-function 3						
Sub-function 4						
Sub-function 5						
Sub-function 6						
Sub-function 7						
Sub-function 8						

Figure 6.12: Example of a morphological chart representing eight-sub-functions and six sub-solutions (Börekçi, 2018)

Even though every solution can fulfil the function, there need to be conditions to rank the solutions.

Examples to do this can be looking at the price; which product is the cheapest? or looking at weight or sustainability. For every function, the best solution can be chosen, after which it is common to draw a line between the solutions that fit every function the best. Also, multiple lines can be drawn when exploring multiple options, connecting, for example, all the cheapest solutions, or the lightest solutions. This way, various combinations of solutions can be compared and a final combination can be chosen.

Circular physical elements

In section 5.1, key indicators with regard to circularity were addressed. Out of all these indicators, material choice is the most commonly used physical indicator when it comes to circularity. This is because lifetime and use frequency are requirements, for determining a design strategy. Modularity and reliability come into account in the logical span. Material choice is a means to meet the logical structure, functions and requirements. Cost is something which is often a requirement, plays a role when determining the logical structure and is a property of a certain material which can play a big role when choosing materials. It has been stated multiple times, but during design, the circular inflow of materials is very important; this can determine half of the circularity of a product. In order for a shipbuilding company to acquire pre-use materials, it is important to have good contact and agreements with suppliers. These suppliers have to do the same with their suppliers, and so on. Good communication is key in order to make sure the source of the materials is known and validated.

In order to help companies in documenting, the Dutch government has set requirements on reporting to help purchasers in acquiring circular materials. With the Socially Responsible Purchasing criteria, a company can set their ambitions (Rijksoverheid, 2023). The use of a higher percentage of circular materials is seen as ambitious and guidelines have been set on which elements a buyer should focus on. Examples of reporting requirements are:

- What percentage, based on mass, of the total product is made of circular material, and what kind of circular material (reused, recycled, etc.).
- Which parts of the system are reused parts.
- What is the origin and previous function of the reused products.

Once pre-used materials have been selected, it is equally important to make sure materials can be repaired and, at the end of life, reused. To select materials and other elements for every design strategy, it is recommended to use the annex drafted by European Commission (2023b). This shows an overview of every design strategy translated into physical aspects.
A few examples of physical elements that are connected to the strategy of design for recyclability in the annex are:

- single polymer or recyclable polymer blends are used;
- plastic enclosures do not contain moulded-in or glue-on metal;
- materials which cannot be recycled together are easy to access and have the ability to be separated;
- parts of the product containing substances, mixtures and components that are to be removed during depollution are easy to identify, such as through marking for sorting provided by the manufacturer, and visible on the product;

The document can be a good guideline for the designer to select materials but also to include other circular aspects.

Product specifications

For circular design, there is a higher urge to reach a higher level of detail during the design phase. During "normal" design it might be enough to specify the need for, for example, a pipe with a certain length and diameter. In the case of circular design, it is important to also specify the material the pipe needs to consist of and in which way it should be attached to other parts of the system. However, this does not mean that every system needs to be designed until no further breakdown of parts can be made, but one should constantly check whether there are sub-systems, components or parts available on the market that meet all the set requirements and functions. How this process works is visualised in Figure 6.13. Every time the requirements, functional and logical structure have been defined, the market or in-house availability of a physical element should be checked that meets the RFL structure. In case it is not available, the RFL structure should be brought to a deeper level of detail. In case there is no further level of detail possible then it should be checked if multiple parts or components can be combined into a logical module. This stresses the need to constantly make the connection between the physical and logical analysis.

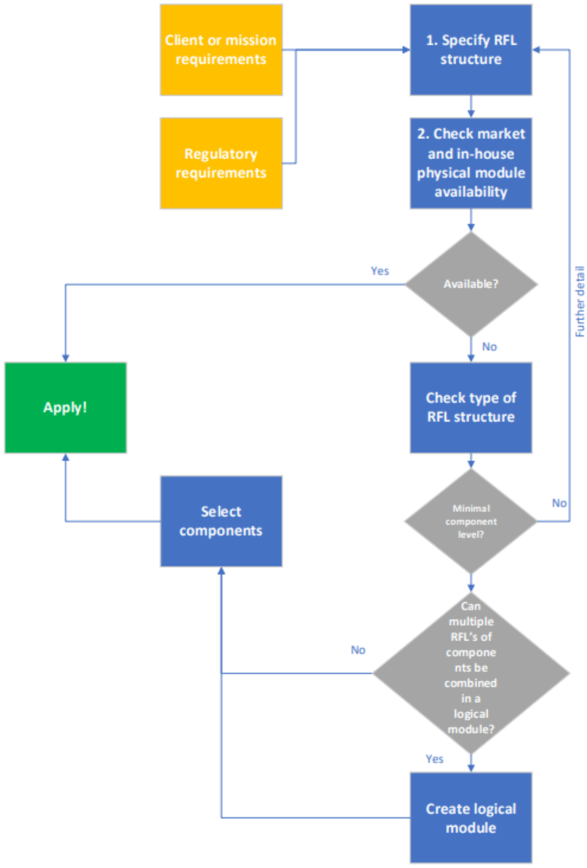


Figure 6.13: High-over process of physical selection and logical model creation (Vink, 2022)

Supplier selection

Once the RFL-structure has been defined and an image of the physical form has been drafted, a supplier must be chosen to deliver the product. Often there are multiple suppliers that can deliver a system. From conversations with the purchasing department at Damen Shipyards, it became clear that at this moment Damen Shipyards focuses on logistics and location, technical value and quality when selecting a supplier (S. Ketting, personal communication, September 29, 2023). Sustainability is slowly becoming a criterion of this selection process. For the selection of suppliers purely based on sustainability, an in-house questionnaire is already available at Damen Shipyards. For circularity a similar questionnaire is drafted by use of the sustainability questionnaire, the input needed for the MCI calculation and the general circular economy principles.

A measurement method is proposed to compare the different suppliers that offer similar systems that match the RFL-structure that was established. The comparison of the suppliers can be, just like the life cycle of a product, done in three phases; The inflow, lifetime and outflow of the company. This assessment can be done by answering questions on the corporate level and on the product level. In case the answer to a question is "Yes", the supplier will get a point. When comparing two suppliers, the one with the most points scores best in terms of circularity. In terms of ranking circularity, the order of the 10R framework should be considered so suppliers that reuse and repair products should be preferred over suppliers that only recycle. At this moment, it might be hard to get information from suppliers on these topics since questions about circularity are not very common yet when selecting suppliers. However, from 2024 on it is obligatory for companies to report on circularity in their CSR report so more and more companies will need to gather information on this topic.

Corporate:

- Does the supplier have a circularity policy/strategy?
- Does the strategy reach further than their own inflow process?
- Is there information available on the total weight of products and materials used in the production

processes, including the percentage of reused or recycled products and materials used in the manufacturing process?
- Does the supplier have a waste management system?
- Does the supplier take back used systems to reuse, repair, refurbish, remanufacture, repurpose or recycle them?
- Has the supplier taken any actions to prevent or mitigate actual or potential impacts arising from resource use and circular economy?

Product:

- Is there information available on the composition of the product? Are there reused or recycled materials present?
- Has the system been designed from a life cycle perspective? of which an end-of-life plan is an example
- Does the system have a circular certification? Examples of circular certifications are Cradle2Cradle, EU Eco Label, Global GreenTag, JTC10, etc.
- Has the product been designed along the circular principles of Refuse, Reduce and Rethink? Examples are minimisation of material use, refusal of virgin materials, etc.
- Has the product been designed along the circular principle of Reuse? Examples of this are the use of materials that have long durability, a system that is easily maintainable by being able to access all parts of the product, a system that has a timeless design and that is reliable. Ideally, the supplier is willing to take back the product at all times in order to be able to let it be reused by a new customer.
- Has the product been designed along the circular principles of Repair? Examples of features are the choice for a repairable material, a simple design that is easy to take apart with standard tools or ideally even no tools, consisting of standardised parts and of which the cost of repair is significantly lower than the cost of replacing the system.
- Has the product been designed along the circular principles of Refurbishment and remanufacture? This also means a system that is easy to disassemble and put back together and of which spare parts are available. Next to that, a flow back to either the supplier or another player should be in place to return the used systems and be able to refurbish or remanufacture them.
- Has the product been designed along the circular principles of Repurpose? Examples of such systems are ones that are easy to disassemble, of which the components and parts are of good quality, systems that are designed for multiple functions, etc.
- Has the product been designed along the circular principle of Recycle? Examples are products of which the different materials can be separated and which in itself are made of materials that can be recycled. Next to that, a loop should be in place to make sure that the materials will eventually end up at a recycling facility.

Circular business models

Even though it might not directly be a physical property of a system, business models will be addressed in this section as well since it can influence the choice between two materials regarding circularity. There a multiple business models that support the principles of the circular economy. In this section, the business models will be explained and a method of choosing a business model for the designed system will be presented. Atasu et al. (2021) define that most companies that focus on the circular economy use business models that are a combination of three basic strategies. The three basic business models are:

- Retain Product Ownership (RPO)
- Product Life Extention (PLE)
- Design for Recycling (DFR)

Retaining Product Ownership is the classic version of a producer leasing or renting its product to the customer instead of selling it. This means that the producer is also responsible for their product once the consumers are finished with them. RPO can be a valuable strategy for companies that offer complex products with a lot of embedded value. For the producer, more investments are needed in after-sales and maintenance. This can be more expensive for them than a strategy of selling and replacing, which will ultimately reflect on the customer. The RPO strategy can also be a good model for simpler products which are expensive and seldom needed. An example of this is renting out tuxedos for promgoers.

The Product Life Extension focuses on designing products that last longer, enabling the reuse of products. Because this means that there will be fewer purchases over time, it might not seem like a profitable business model for manufacturers. However, durability is a key competitive differentiator and is a viable reason for premium pricing. Next to that, PLE can help companies to prevent their customers from defecting to a rival brand.

Lastly, Design For Recycling focuses on redesigning products and manufacturing products to maximise the recoverability of the materials that are involved for use in new products. For this strategy to succeed partnering with companies that can use the recovered materials or have specific technological expertise.

To determine which combination of the three strategies is the best for a company or system, practical and very specific questions need to be asked. Even then, the circularity strategies require careful calculations of value and costs and a certain amount of experimentation and piloting to assess the feasibility of a strategy. In order to help companies, two questions are proposed:

1 How easy is it to get my product back?
2 How easy is it to recover value from my product?

In order to have a successful answer to the first question, two key elements are required to have a successful reverse supply chain; public participation and infrastructure. Without these two factors, access to used products for circularity will be a challenge. Another important element to take into account is the existence of a secondary market where the used products and commodities can be sold.

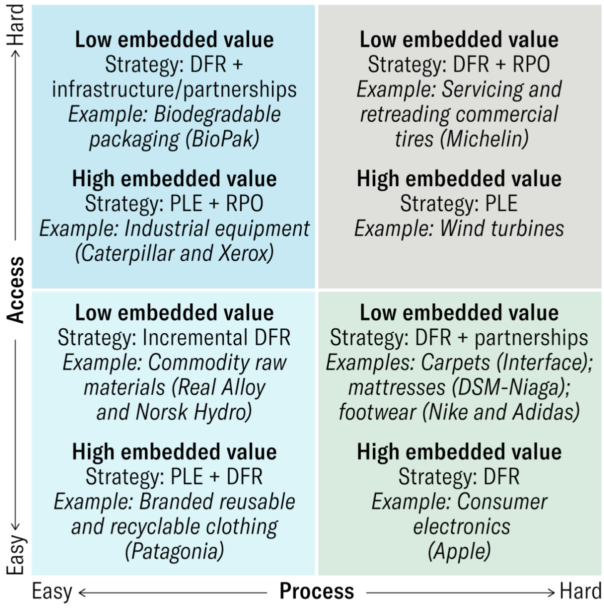


Figure 6.14: Circular Business Strategy Matrix (Atasu et al., 2021)

For the second question, the value of the recovered product depends a lot on the type of product. Extremely heavy or bulky products and those containing potentially hazardous materials are often relatively easy for producers to reclaim legally, but very difficult and expensive to move and recondition. Additionally, it is hard to recover value from products that are intricately constructed. Lastly, the potential of value recovery depends on the availability of solutions for reformulating products in a cost-effective way. By answering these two questions, a company can use a two-by-two matrix that presents the options for creating circular business models. the matrix is shown in Figure 6.14. The vertical axis shows the gradient for the answer to the first question on the ease of getting the product back. The horizontal axis shows the answer option for the second question about the value to be recovered from the product. Depending on the embedded value of the product, a business model can be selected. As can be seen, almost for every product the model of design for recycling is applicable since every product will in the end need to be recycled. For products with a high embedded value that are hard to get back but have an easy way of recovering value, the strategy of retaining product ownership becomes important. Product life extension is an interesting model when the embedded value of a product is high.

6.5.5. Results after step 5

After completing step 5, requirements should have been set that can be translated into functions. After this, the functions can be connected in a logical way and physical solutions can be sought that match the requirements, functions and logical structure. These physical solutions can be sought with the help of a morphological overview whilst constantly checking the RFL structure. After a compatible physical solution has been found, suppliers can be selected and eventually a business model can be linked to the system based on the product type.

6.6. Step 6: Validate the (re)design

System engineering is not a linear approach but can be seen as a process where constant validations between all steps have to be carried out. This is in order to get to a deeper level of detail, but also to make sure all stakeholder needs are still in line with the system being designed. As a way of checking whether or not the physical (sub)system fulfils the desired functions, and whether these functions meet the requirements, a validation matrix can be filled in and to check the circular requirements the level of circularity can be measured. Both methods will be elaborated upon in this section. The connections and validations between the requirements, functions and physical system are shown in Figure 6.15.

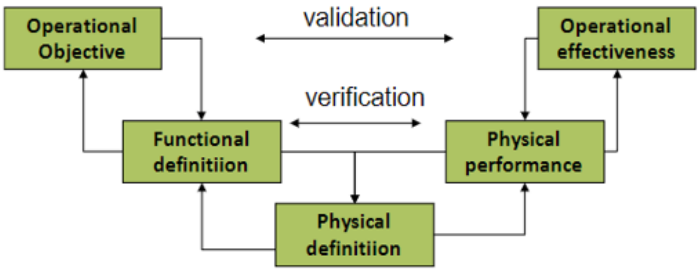


Figure 6.15: A visualisation of the connections between the requirements, functions and physical system (Hopman, 2021)

6.6.1. Validation Matrix

In order to check whether the designed system meets all functions and requirements, a Product Management Map (PMM) can be made. In the PMM multiple matrices are filled out to see what the connections are between requirements, functions and physical elements. An example of an PMM is shown in Figure 6.16.

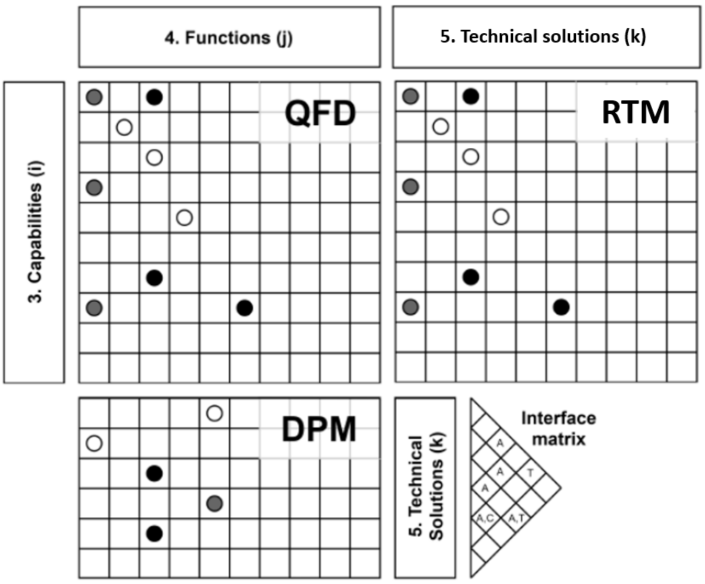


Figure 6.16: Product Management Map (PMM) (Kana, 2021)

The PMM in Figure 6.16 shows four matrices; The QFD, DPM, RTM and interface matrix. QFD is short for Quality Function Deployment and visualises the connection between the requirements and the functions. The connection is visualised by the use of a circle with a certain filling. The meaning of every symbol is shown in Figure 6.17. In case a row of requirements remains empty, it means that no function was coupled to it and the requirement is most likely not fulfilled. The other way around, when a whole column of a function is empty, it shows that the function is fulfilling something that was not required. In this case either the requirements need to be adjusted when the function turns out to be important, or the function is unnecessary and needs to be eliminated. The abbreviation of DPM stands for Design Property Matrix. This matrix maps the relations between the physical solution elements and the functions by use of the same symbols as the QFD. The same here goes for the empty rows and columns; either the physical solutions need to be reviewed or the functions have to be adjusted. RTM stands for Requirement Traceability Matrix and links the requirements of the physical solutions. This is kind of the final check to see if all requirements are met by physical solutions. Once again, in case a row or column remains empty, the physical design should be checked for either missing requirements or over-designing for requirements that were not there.

Lastly, on the right side of the figure, the interface matrix is shown. This matrix evaluates how modules are physically joined together. The joints are indicated by the use of four letters. A, for Attachment; this means that there is a physical connection between two elements. This connection puts the pieces together or connects them physically. T is for Transfer; Transfer means that there is a conduit for power or media to transfer from one module to another. There is C, standing for Command and Control. This means that a component is communicated/controlled by other components. Lastly, there is the S for Spatial. Spatial determines the boundary between modules, referring to the spatial location and volume of a component. The interface matrix is a sort of combined version of the physical and logical architectures shown in Figure 6.3.

QFD/DPM	MIM	Score	Symbol
Strong relationship	High impact	9	●
Moderate relationship	Medium impact	3	◉
Weak relationship	Low impact	1	○
No relationship	No impact	0	

Figure 6.17: Legenda of the symbols used in the PMM (Kana, 2021)

After the PMM has been filled out, the designer can see whether the physical solutions match all functions and requirements and if this is not the case, the designer can adjust the design or the requirements/functions. Also, the matrix may help in showing what requirements and functions need a further level of detail in order to continue with a design, so this matrix can also already be used in the concept exploration phase.

6.6.2. Measuring Circularity

To see whether or not a system meets the requirements in terms of circularity, the level of circularity needs to be measured throughout the design process and at the end of the design process. This can be done following the same procedure as described in Step 3. However, an advantage is that during the design a good overview of the whole system and its connections is already available. This makes it ”easier” to make the breakdown of systems, sub-systems, components, etc. For this step, it is very important that, in case the circularity was also measured in step 3 an existing system, the same level of detail for the measurement is taken. Otherwise, the comparison is not fair and can result in an unreliable outcome. In case the outcome of the circularity measurement is not sufficient to meet the requirements, the design is not finished and there is a need for a designer to continue making alterations until all requirements are met.

6.6.3. Results after step 6

After completing the sixth step, the goal is to have a filled-in validation matrix without any empty rows and columns. Also, a remeasurement of the circularity should have been made which can be compared to the first measurement which was done in step 3. After completing this step, the whole framework has been completed and the desired outcome of the whole framework is a system that complies with all set requirements and functions and, if applicable, is more circular than the current solution.

7 Case Study: The Wheelhouse

To test the suggested framework, a test case is executed. This test case will focus on the wheelhouse of a vessel. The choice for the vessel and the wheelhouse will be elaborated upon in section 7.1. All steps of the framework will be completed and afterwards, an evaluation of the framework will be performed.

7.1. Step 1: Identifying the overall goal and mission

To start the case study, the overall goal and mission of the to-be-designed system need to be selected. This goal and mission are often defined by a client that has a need for a (re)new(ed) system or is caused by a change in regulations which makes the existing system obsolete. In this case, Damen Shipyards wishes to create a new design for a wheelhouse. What this means regarding general and circular requirements will now be explained.

7.1.1. General goal

The goal chosen for the system is: To create a space from where the crew can operate and control the complete vessel. The choice for this goal is consistent with the capabilities of a current wheelhouse. This was chosen because Damen wants to redesign its wheelhouse in terms of both looks and feel while considering the circular economy principles. In 2019, Damen made, in cooperation with the company VanBerlo, a design of a new wheelhouse for a tug where more space and comfort were created for all sailors on board. The design was mostly graphic, taking into account the required equipment, rules and regulations and comfort. One of the aspects not taken into account was circularity and with that the choice of materials and products. Damen aims to pick up this specific project again, where a new constraint in the design will be added; circularity. The type of wheelhouse is in this new case not of great importance since most components in a wheelhouse of any kind are the same.

7.1.2. Circular goal

Regarding circularity, the overall mission and goal is to design and build the systems in the most circular way possible whilst following the 10R principles for a circular economy. This does not mean that the goal is to make a 100% circular product or system, but that the system should be as circular as possible with the current technologies whilst also meeting the general requirements.

7.1.3. Continuation

The descriptions of the general and circular goals are not very extensive but this is also not necessary. The goal of step one is to see whether or not there is an existing system that already fulfils the goals. It can be concluded that there is a system present on the RSD2513 tug that meets the general goal but which does not meet the circular goal. Therefore the current wheelhouse will be assessed in Step 2 and 3 of the case study. The choice for the RSD2513 tug will be elaborated upon in the next step.

7.2. Step 2: Identifying and breaking down the system, sub-systems, components, sub-components and parts

As said before, the overall goal and mission match the current design of a wheelhouse. To see what the current system looks like, it needs to be broken down into sub-systems, components, sub-components and parts. To do this, a wheelhouse needs to be chosen since every vessel has a different wheelhouse. As explained in step one, Damen Shipyards made a new, graphic design for a wheelhouse of a tug in 2019. This design focuses on functionality space and comfort but circularity is not taken into account. Next to that, the design has not been further engineered nor put into practice so this design can be used as inspiration for the new wheelhouse design. Because the design of the "new" wheelhouse is in line with the design of the current tug boat type RSD2513, this is the vessel type that will be assessed. RSD stands for Reversed Stern Drive and 2513 stands for the length and width of the vessel; 25 meters long, and 13 meters wide.

Figure 7.1: Visual of the RSD2513 (Damen Shipyards, 2023c)

7.2.1. System Boundaries

To see what is in the wheelhouse of an RSD2513, the first step is to define the boundaries of the wheelhouse as a system. The literal definition of a wheelhouse according to the Oxford Dictionaries (2023) is: "a small cabin with walls and a roof on a ship where the person controlling the direction in which the ship moves stands at the wheel" (Oxford Dictionaries, 2023). To limit the physical boundaries of the wheelhouse, it has been chosen to view the wheelhouse as everything inside (and including) the superstructure of the wheelhouse until the floor of the bridge deck. By use of arrangement plans, parts lists, the standardisation specification and part drawings all that is inside the wheelhouse can be identified.

7.2.2. System levels

The wheelhouse is seen as the main system here and will consist of sub-systems. These sub-systems are identified by the information available at Damen Shipyards. The sub-systems are identified by identifying major parts of the system that perform similar functions. The sub-systems' names might sound like they are components or parts but they are sub-systems that consist of multiple components and these components again out of parts. Several sub-systems were identified:

- Air Conditioning	- Chair(s)	- Chart table
- Walls	- Ceiling	- Doors
- Floor	- Consoles	- Windows
- Navigation equipment	- General equipment	- Lightning and sockets
- Switchboard	- Ventilation	- Superstructure

This means that every sub-system will again consist of components. However, it is almost impossible to discuss every component in the wheelhouse and after that every part since there are so many components and parts. Therefore it has been chosen to select five sub-systems and examine them further. Five have been selected to identify the differences in functions but also in circularity. Of these five sub-systems, in the end, only the system with the lowest circularity level will completely go through the framework, but that will be elaborated upon in a later phase. The chosen sub-systems are:

- The captain's chair: The "main" chair has been selected because it is very different from the new design Damen made and will therefore first be assessed in this current form.
- The consoles: These are also very different in the new design. Next to that, they are complex, housing lots of electronics and equipment.
- The windows: The windows are complex but also very unique for the wheelhouse, no other section of the vessel has these windows, contrary to the floor, doors or walls.

- Superstructure: The superstructure is the heaviest sub-system of all sub-systems. Therefore it will have a big influence on the overall circularity assessment since the MCI method is based on weight.
- The floor: Damen Shipyards has recently selected a new floor supplier so this new floor will be analysed, also because the floor is quite heavy compared to other sub-systems.

A similarity the consoles, windows and superstructure have in common is that they are designed in-house by Damen Shipyards. This means it is possible to have influence in the design process, contrary to other sub-systems such as the navigation equipment which is all bought from suppliers. To also have sub-systems which are not designed by Damen itself, the chair of the captain and the floor are added. These examples can be used to set guidelines for selecting suppliers but also for suppliers on how they can improve their product in terms of circularity.

Unfortunately, information is hard to find about the systems and not every detail is known. Therefore the assessment can only go as far as the information allows, meaning the level of detail differs per system. Let's have a look at all systems and further break them down into components and parts.

Captain's chair

Starting with the chair of the captain. The chair is manufactured by AluTech. All information used in the breakdown and analysis is therefore also coming from AluTech documents. The chair consists of two components; A seating chair and a deck rail (with a wagon) which the seating chair is mounted onto (Alu Design and Services AS, 2012). This deck rail makes it possible for the captain to move in between the consoles. The seating chair is made of a frame with cushions for the seating part, back and armrests. The deck rail consists of the rail itself, which is flush mounted onto the floor of the wheelhouse. And there is a wagon and sliding parts which make the movement smooth. To cover the rail there are snap-in covers and there is a brake cable to ensure the chair can remain in the desired position. The overview of all components and parts is shown in Table 7.1.

Sub-system	Components	Parts
Chair captain	Seating chair	Seat cushion
		Backrest
		Armrest top
		Extruded frame
		Cast frame
		Connecting bolts
	Deck rail	Rail
		Sliding parts
		Wagon
		Connecting bolts
		Snap in covers
		Brake cable

Table 7.1: The breakdown into components and parts of the sub-system "Captain's chair"

To give a spatial overview of how all components and parts are connected, a combination of a logical and physical architecture is made. This is shown in Figure 7.2. To get a better understanding of the chair, a visual is also included next to the architecture in Figure 7.3.

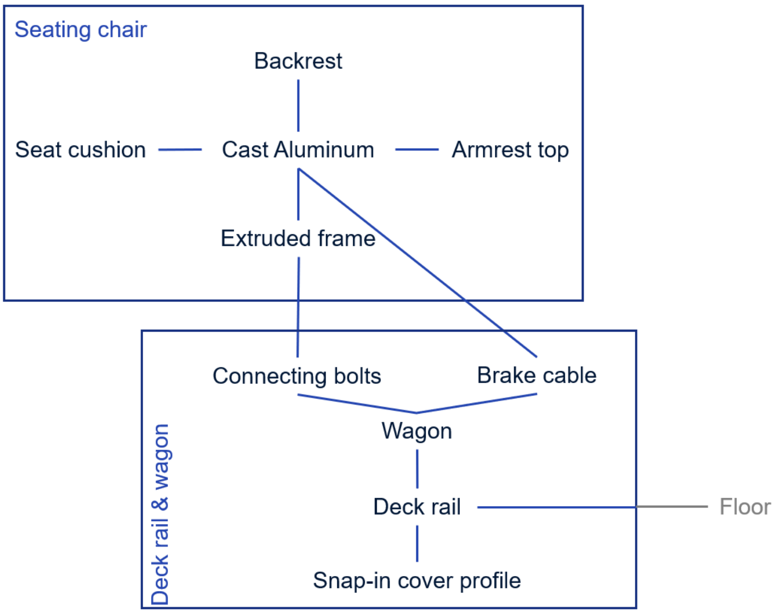


Figure 7.2: Logical and Physical Architecture of the Captain's Chair

Figure 7.3: Visual of the two chair components; the seating chair and deck rail (Alu Design and Services AS, 2012)

Consoles

The consoles have been designed in-house by Damen and house a lot of electronics and navigational equipment. However, often not the whole system is housed in the console but only the controls are located in the consoles whilst the main processor of the system is housed somewhere else on board. Examples of controls which are located in the consoles of the RRD2513 are the emergency stops, radar, searchlight, winch controls, etc. These controls are located in two "standard" consoles with an aluminium top plate that is adjusted dependent on the type of controls that have to be located in it. To assess the consoles properly and in a representative way, it has been decided to not take into account the controls that are located in the top plate of the console for the following reasons:

- The controls are all not designed by Damen. Therefore it is very hard to get information on every system. This would take an enormous amount of time if all controls have to be examined properly since information will have to come from suppliers, which also might not have the information needed since they also make use of suppliers to get their parts.
- There are too many different controls to assess thoroughly in the time provided. The level of detail of every control is very complex consisting of many, many parts.
- The systems that are controlled stretch out through the whole vessel. Examining only the button which is present in the wheelhouse to control, for example, the winch would not be fair; the whole sub-system of the winch should be assessed. However, doing this for every sub-system which is connected to a control button in the console is not possible.
- The console itself, without all controls, already consists of multiple parts and materials, providing an already challenging case which can be used to test the proposed framework. There is no need to take all controls into account to ensure the framework is sufficient.

Looking at the console itself, the sub-system is the ASSY console. ASSY means Assembly. There four components can be distinguished. The other components present can be seen as the controls and will not be taken into account for the reasons just discussed. The ASSY Console then again consists of many parts. All parts have been listed in Table 7.2.

Table 7.2: The breakdown into components and parts of the sub-system "Consoles"

Sub-system	Component	Parts
ASSY Console	Hatches	Rubber profile hatch
		Rubber profile ventilation hatch
		Hatch with ventilation
		Hatch
		Compression latch
		Cam, without catch, without recess
	Console Enclosure	Handrail
		Lower console part
		Upper console part
		T-bar lower console part
		T-bar upper console part
		Metal mounting plate: divider
		Metal mounting plate: Long side
		Metal mounting plate: Front
		Metal mounting plate: short side
		Stud bolts
	Fan	Fan DC
		Fan cover
	Top plate	Gas spring
		Rubber profile
		Top plate
		Hinge

Looking at Table 7.2, it can be concluded that the level of detail of the console is way higher than the level of detail of the chair. This is because the console is designed and assembled by Damen Shipyards itself, whilst the chair is delivered by AluTech and only the Components have to be put together instead of all parts. This comes to a greater level of detail which is very helpful for the next step where the circularity will be assessed. Similar to the chair, a logical and physical breakdown has been made for the console, shown in Figure 7.4. To get a better feeling for the console, the visual is also added in Figure 7.5.

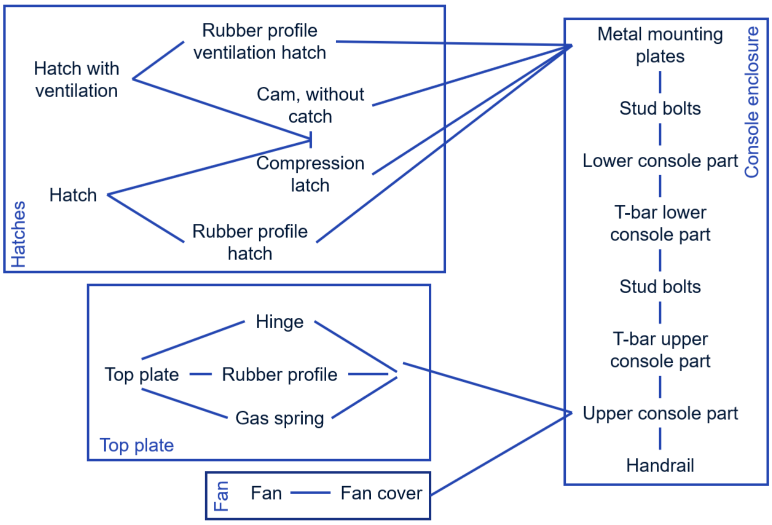


Figure 7.4: Logical and Physical Architecture of the Console

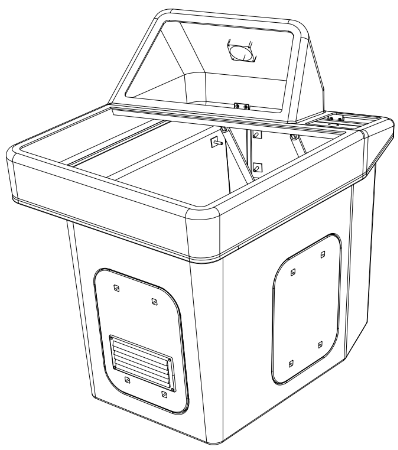


Figure 7.5: Visual of the Console (Damen Shipyards Group, 2020)

Windows

Similar to the chair and console, the windows can also be broken down into components and parts. The windows also include sunscreens and window wipers. Because every window consists of the same components and parts, the breakdown is shown for one window. In reality, the windows differ in size but this does not change the composition of the windows. The windows can be differentiated into vertical windows and sky windows. The difference between the two is the location and the fact that the sky windows do not have windows wipers, the vertical windows do. The different components are supplied by three different suppliers. The breakdown is shown in Table 7.3.

Table 7.3: The breakdown into components and parts of the sub-system "Windows"

Sub-system	Components	Parts
Windows	Glass windows	Window panes
		Frames
	Window wipers	Window wiper motor
		Window wiper blade
		Window wiper arm
	Sunscreens	Bracket for solar curtain
		Solar screen
		Cheese head screw
		Self adhesive film

At first glance, this sub-system might look quite simple as it consists of not so many parts. However, every part in itself, such as the window wiper motor and window wiper blades will also consist of smaller elements. It was decided to not go into a further level of detail than the current breakdown because the parts as now defined are all purchased parts. The window wiper motor is from a different supplier than the wiper blades and the solar screens are again from another company. This would mean that a lot of time would go into further breaking down the system, also because the parts in themselves are quite complex. Once again, a logical and physical architecture has been made for the windows, shown in Figure 7.6. Next to that, a visual is shown in Figure 7.7.

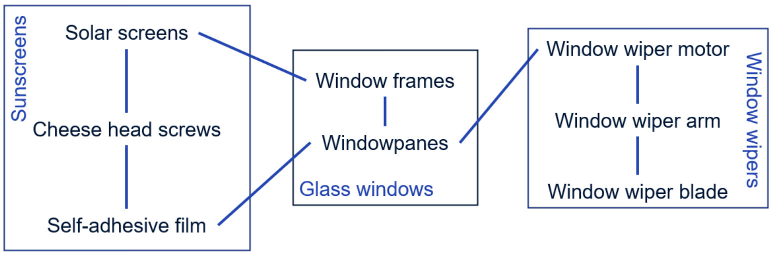


Figure 7.6: Logical and Physical Architecture of the Windows

Figure 7.7: Visual of the Windows (Matterport, 2023)

Superstructure

The last sub-system that is analysed is the superstructure. The superstructure includes the superstructure itself in terms of steel plating and stiffeners. Next to that, there is insulation present, attached to the steel plates and stiffeners. The breakdown into components and parts is shown in Table 7.4.

Table 7.4: The breakdown into components and parts of the sub-system "Superstructure"

Sub-system	Components	Parts
Superstructure	Superstructure	Plates
		Stiffeners
	Insulation	Insulation material
		Insulation fastener
		Adhesive tape
		Coating

Out of the four selected sub-systems, this is the "simplest" sub-system since the parts cannot be broken down any further and there are not a lot of different parts to be analysed. However, this is the sub-system with the highest weight and will thus have the biggest influence on the calculation of the circularity in the next step. The architectures are added in Figure 7.8 and the visual of the superstructure is shown in Figure 7.9.

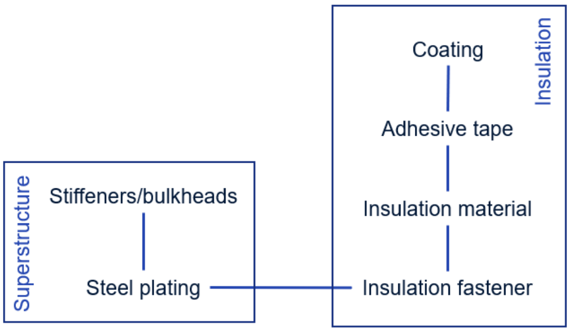


Figure 7.8: Logical and Physical Architecture of the Superstructure

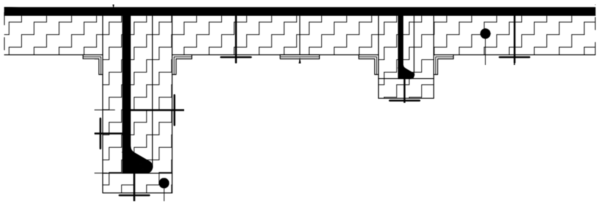


Figure 7.9: Visual of the Superstructure (Damen Shipyards Group, 2021)

Floor

The floor that will be assessed is not the floor presented in the RSD2513 at this moment, but the floor present in the ASD2312. This is because the floor in the RSD2513 is supplied by a certain supplier, whilst Damen Shipyards is shifting toward the new supplier for their standardisation of the tug: Sika. To look at the possibilities of this floor on board the RSD2513, this newer floor will be analysed. This new standard is already present on the ASD2312 and this vessel has dimensions comparable to the RSD2513, therefore the floor on this vessel will be analysed. All the components and parts are identified and shown in Table 7.5.

Table 7.5: The breakdown into components and parts of the sub-system "Floor"

Sub-system	Components	Parts
Floors	Floating floor	Two-component polyurethane cast floor
		Two-component epoxy primer
		Electro galvanized steel plate (2mm)
		Bonding adhesive
		Electro galvanized steel plate (3mm)
		Steel strip
		Insulation
		Self-levelling mortar
		Primer
		Visco Elastic Mortar (2mm)
		Glue
	Floor covering	Two-component seal layer
		Coating, Coloured chips
		Two-component seal layer
		Two-component decorative resin
		Synthetic floor covering

As can be seen in the breakdown, the floor consists of a lot of layers made from a lot of different materials. The layers are glued together and quite some layers are cast. The floor is made of primers, followed by insulation, covered with steel plates, and on top of that cast floor covering. The architecture and visual of the floor are shown in Figure 7.10 and Figure 7.11.

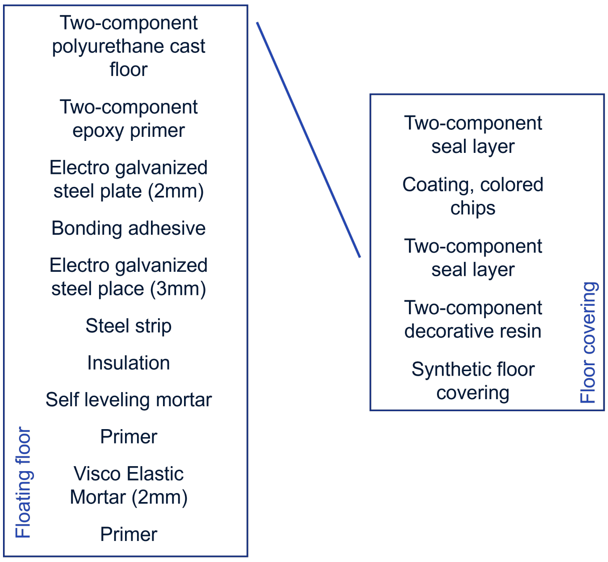


Figure 7.10: Logical and Physical Architecture of the Floor

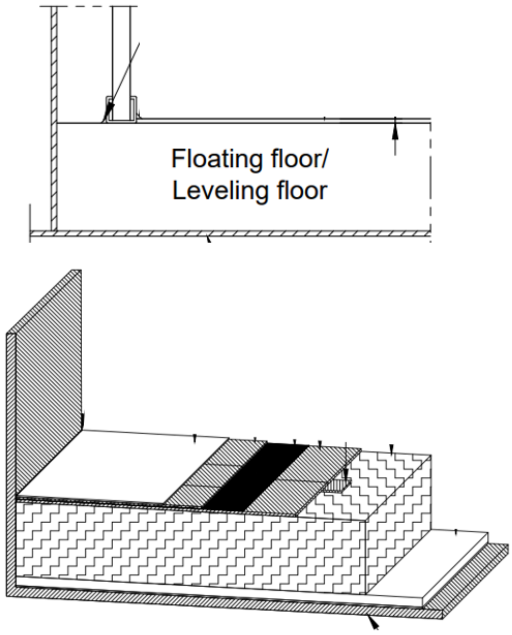


Figure 7.11: Visual of the floor. On in the upper figure the floor covering is shown and in the lower figure the floating floor is broken down in the different layers (Sika and Damen Shipyards, 2022).

7.3. Step 3: Determining the current circularity level

The circularity level of current sub-systems will be analysed to show the need for a redesign when the circularity level does not meet the requirement. To measure the circularity of the five sub-systems, the weights need to be known, but also the information about the key indicators needs to be acquired.

7.3.1. Weight

To acquire the weight of different sub-systems, the ”weight calculation” of the whole vessel can be used. In the weight calculation, the weights of all systems in the vessel are listed per system code. The system codes are specific for Damen Shipyards and divide the vessel into sections such as code 100 for the hull and outfitting, or code 200 for the main machinery. In every big code, there are further variations for the sub-systems such as code 151 for the fenders or code 712 for all walls onboard. Unfortunately, for this case study, the codes are not ordered per space but per system type. This makes it harder to get to, for example, the weight of only the floor in the wheelhouse, instead of the weight of the floor laid in the complete vessel. Next to that, the weight of more specific sub-systems is given for the whole system instead of per component or per part. Therefore also suppliers of the sub-systems were asked about the weights of the sub-systems, components and parts. Eventually, all weights could be gathered to the level of detail shown as shown in Table 7.6.

Table 7.6: The mass of the sub-systems

System	Sub-system	Components	Parts	Mass [kg]
Wheelhouse	Chair captain	Seating chair	Seat cushion	3,50
			Backrest	6,5
			Armrest top	38
			Extruded frame	
			Cast frame	
			Connecting bolts	
		Deck rail	Rail	32
			Sliding parts	
			Wagon	
			Connecting bolts	
			Snap in covers	
			Brake cable	
	ASSY Console	Hatches	Rubber profile hatch	510
			Rubber profile ventilation hatch	
			Hatch with ventilation	
			Hatch	
			Compression latch	
			Cam, without catch, without recess	
		Console Enclosure	Handrail	
			Lower console part	
			Upper console part	
			T-bar lower console part	
			T-bar upper console part	
			Metal mounting plate: divider	
			Metal mounting plate: Long side	
			Metal mounting plate: Front	
			Metal mounting plate: short side	
			Stud bolts	
		Fan	Fan DC	
			Fan cover	
		Top plate	Gas spring	
			Rubber profile	
			Top plate	
			Hinge	
	Windows	Glass windows	Glass panes	1655
			Cover lists	25
			Retaining list	107
			Frames	850
		Window wipers	Window wiper motor	92
			Window wiper blade	
			Window wiper arm	
		Sunscreens	Bracket for solar curtain	90
			Solar screen	
			Cheese head screw	
			Self adhesive film	
	Superstructure	Superstructure	Plates	4784
			Stiffeners	
		Insulation	Insulation material	255
			Insulation fastener	
			Adhesive tape	
			Coating	
	Floors	Floating floor	Two-component polyurethane cast floor	590
			Two-component epoxy primer	
			Electro galvanized steel plate (2mm)	
			Bonding adhesive	
			Electro galvanized steel plate (3mm)	
			Steel strip	
			Insulation	
			Self-levelling mortar	
			Primer	
			Visco Elastic Mortar (2mm)	
			Glue	
		Floor covering	Two-component seal layer	22
			Coating, Coloured chips	
			Two-component seal layer	
			Two-component decorative resin	
			Synthetic floor covering	
	Others	-	-	±3000

7.3.2. Gathering information

The way the information was gathered to perform the MCI calculation will be elaborated upon in this section.

Inflow

For the inflow, the most important indicator is the material choice. Information about the material of the components and parts can be often found on the bill of material of the sub-systems. However, the process of figuring out exactly what part of the material inflow which is stated on the bill of material is circular, is very hard. To determine the source of the material that is used in the five different sub-systems, the suppliers of the parts were contacted. This is because, for example, the glass for the windows is delivered by a different supplier than the sunscreens or window wipers. To get the information needed to fill in the MCI calculation, the questions that were proposed in the framework were asked. All suppliers responded and answered the questions, but unfortunately, they were not always able to answer the questions in detail. Where the data was unavailable, use was made of the material database of Ansys Granta Edupack. The averages as shown in Figure 7.12 were used as inflow percentages.

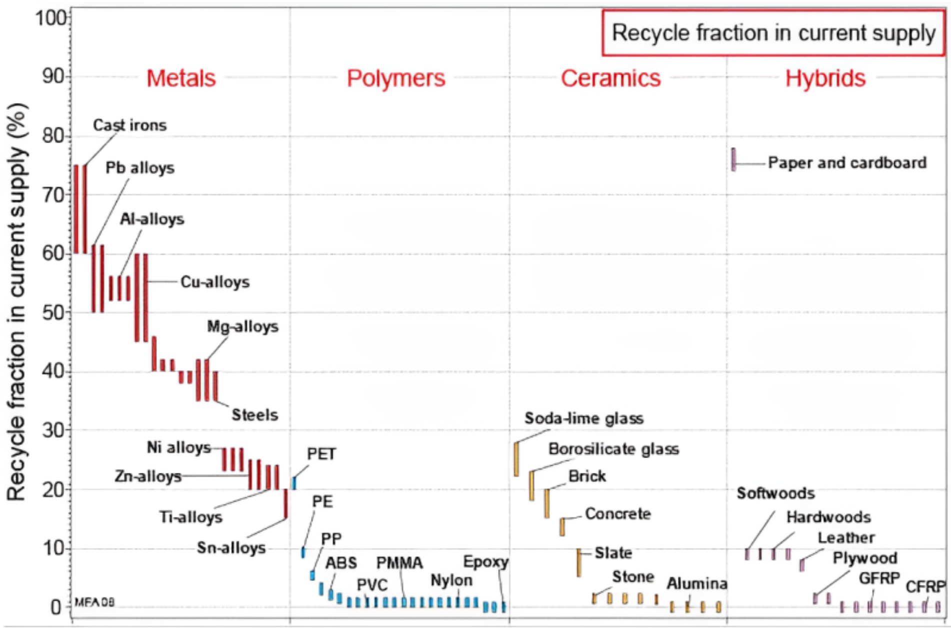


Figure 7.12: The fraction contribution of recycled material to current consumption (Ansys Granta Edupack, 2006)

Utility: Lifespan and Use frequency

Damen Shipyards designs its vessels for a lifetime of twenty years. This might not hold for every system or sub-system on board since some might need repairs or replacement before the twenty years are over. Suppliers were contacted to get information about the lifetime and use frequency of their products. Because many of the sub-systems selected are very specifically for maritime applications, it is hard to find an industry average for both the lifetime and use frequency of sub-systems. There are for example very few producers of marine floors or windows for maritime applications. The lifetime of the sub-systems that were selected is therefore very likely to be equal to the industry average because they set the industry average. For this reason, it was chosen to not use the calculation of the utility (X) in the calculation of the MCI because the value for the utility will be equal to 1. This means that the MCI is calculated only by $1 - LFI$. The lifespan and use frequency are mentioned in the analyses of the different sub-systems to get a feeling for the differences in terms of lifetime for the sub-systems.

Outflow

Because the systems that are analysed are not yet at the end of their lifetime, the outflow is not 100% sure. However, looking at the key indicators we can make an estimation or determine the potential regarding the destiny of the sub-systems at the end of life. For the outflow of materials, no standardised database exists and common practices were researched that will be discussed per sub-system.

7.3.3. MCI of the five sub-systems

In this subsection, the calculation input that calculates the MCI of the sub-systems will be elaborated upon. Every sub-system will be discussed separately. The full overview with all numbers used in the calculation is shown in section D.1.

Captain's chair

The captain's chair is fabricated by Alutech. The main parts in terms of weight are the aluminium frame, the backrest and the seat cushion. Contact with Alutech made it clear that the aluminium is produced by Norsk Hydro (K. Aas, personal communication, August 1, 2023). Norsk Hydro guarantees a recycled material inflow in their aluminium of 75% (Hydro, 2023). The seat cushion and backrest do not consist of any previously used materials and are both made of 100% virgin material. The snap-in covers are made of plastic which has not been recycled before as far as Alutech knows. However, it is known that the supplier that delivers the snap-in covers to Alutech recycles the plastic at their end.

Alutech states that the seating cushion is at this moment replaced approximately every five years. The back cushion has a longer lifetime and is replaced every ten to fifteen years. The aluminium frame lasts as long as the vessel; approximately 25 to 30 year

The chair does not contain any welds and is bolted together. This means that it can be easily dismantled at the end of life into different parts again. Because the parts made from aluminium can be separated from all other materials, they can be completely recycled (European aluminium, 2020). The seat cushion, armrest and backrest are made of polyurethane integral foam and covered with leather. Leather cannot be recycled and is most often incinerated (Ansys Granta Edupack, 2022b. Polyurethane foam and the plastic from the snap-in covers can be recycled for 100 per cent (Marson et al., 2021)(Goodship, 2007). The MCI that was calculated is equal to 0.79. This means that the chair is circular for 79%.

Consoles

The consoles are produced by Damen Shipyards in Antalya. Due to the fact that no contact was established with them, industry averages were used for the calculation. Since only the total weight is known of the consoles, the inflow distribution is an estimate. The console consists of rubber profiles for the hatches, console parts made of a composite sandwich, and plates and T-bars made of stainless steel. As seen in Figure 7.12, the average recycled content for steel is 37%. For rubber, this number is equal to $\pm 0.1\%$ (Ansys Granta Edupack, 2022c) and for the composite used (Laminated IQ) this fraction is the same (Ansys Granta Edupack, 2022a). It is estimated that the weight of the steel is equal to the weight of the composite and rubber together. Therefore the inflow will consist of 18.5% recycled materials and 81.5% virgin materials.

The lifetime of the console is equal to the lifetime of the ship; approximately 20 years. During the lifetime, repairs are possible due to the fact that the consoles are assembled by the use of bolds and nuts. Next to that, the consoles are covered with an aluminium top plate where all the buttons for navigation and other necessary equipment are located. This aluminium top plate can easily be lifted by the use of gas springs to reach the equipment inside the consoles.

Looking at the outflow of material, all different material types can be separated. The consoles might have the potential for refurbishment or remanufacturing depending on the state of the components and parts at the end of the lifetime. However, at this moment that is not the common practice. The materials can be separated for recycling. The steel plates can be recycled for one hundred per cent (Björkman and Samuelsson, 2014). Recycling composites into new composites of the same quality is not possible but can be used in other applications such as adding it to cement kilns (Job, 2013). Rubber can go through size reduction that results in powder and can then be melt blended with thermoplastic resins to produce Thermoplastic Elastomer (TPE) compounds (Fazli and Rodrigue, 2020). Therefore the outflow of the consoles could be recycled for 100%. The total MCI that comes out of all these inputs is 0.59, meaning a circularity level of 59%.

Windows

The glass windows and their frames are delivered by van Wingerden. Contact with van Wingerden made clear that the glass is not made of pre-used materials, not even recycled, because this is not possible due to contamination and the colour (J. van Meeteren, personal communication, August 30, 2023). The new glass has to be clear with a maximum light transmittance. The frames are made of mild steel and the covers are made from stainless steel (AISI 316). No information is provided about the origin of the steel so industry averages were used. An average of 37% recycled steel was used, assuming 67% of the steel is virgin. The window wipers consist of AISI coated with Polyester Epoxy and finished with rubber for the wiping part touching the window. Rubber and Polyester both have recycled inflow of 0.1% according to Ansys Granta Edupack (2022c) and Ansys Granta Edupack (2022d). The solar screens are a combination of aluminium boxes with plastic bars and a polyester film in the middle (G. Zhou, personal communication, September 12, 2023). Plastic has an average recycled content of 0.6% (Ansys Granta Edupack, 2022e).

The lifetime of the glass windows is equal to the lifetime of the vessel, the window wipers and the solar screens have a lifetime of 3 to 5 years under proper conditions. The window wipers wear out, just like regular car window wipers do. For the solar screens, the lifetime is short due to the sun damaging the glue that is in between the polyester film layers. The metal and plastic parts of the curtains last longer.

The glass windows can be completely recycled at the end of life; the steel and glass can be separated again and sent to the appropriate recycling facilities. An interesting note is that even though glass can be fully recycled, in practice it almost never happens and the glass is crushed together with other building materials and put into landfills or recovered according to Glass for Europe (2013). Regarding the window wipers, it is hard to separate the stainless steel and the polyester epoxy coating. All the parts of the solar screens can be separated again. The total MCI of the windows as a sub-system comes to 0.57, a percentage of 57% circularity.

Superstructure

The superstructure itself is fully made of steel and the insulation is a combination of stone wool and steel pins. The steel will be very dominant in the calculation of the MCI of the superstructure because it has a way larger weight than the insulation. The steel has an industry average inflow as discussed before at the other sub-systems of 37% and the stone wool has no circular inflow so the virgin inflow is 100%.

The lifetime of the complete sub-system is equal to the vessel's life. It might only need repairs or replacement in case of unforeseen damages. The use frequency of a superstructure is hard to express, but since the structure is permanently performing its function, it can be said that the use frequency is ”always”.

At the end of life, the steel can be recycled for 100% (Björkman and Samuelsson, 2014) as well as the stone wool (Rockwool, n.d.). There could also be a potential for refurbishment or remanufacturing, but that is not common at this moment. This all results in an MCI of 0.67, so the superstructure is circular for 67%.

Floor

The last sub-system analysed is the floor. The floor is supplied by Sika. As can be seen in Figure 7.10, the floor is built up out of many layers. The most important layers in terms of weight are the insulation layer, the steel plates, and the floor covering with cement and primer. Once again industry averages are used. The inflow for the steel plates has 37% recycled content and 63% virgin material. The insulation layer is made of mineral wool; a glass wool. This has a 100% virgin inflow. Lastly, the cement and primer layers also do not have any circular inflow.

The lifetime of a floor that is provided by Sika is equal to the lifetime of the vessel. In case of damage to the top layer of the floor due to falling objects for example this can be repaired by recoating it.

Unfortunately, the floor is joined together by glue and coated layers. The results of this is a very big challenge in separating the different material types at the end of life. Next to that, the floor is fitted perfectly for the space available in the wheelhouse and is hard to dismantle, so reusing, refurbishing or remanufacturing it for applications onboard other vessels will be hard. This means that the only option for the floor in its current from is to break it out and recover it.

Due to the fact that there is little circular inflow and no circular outflow, the current MCI for the floor is 0.096; 9.6% circularity.

7.3.4. Conclusion on circularity

The total MCI of the five sub-systems that have been analysed comes to 60%. This is mostly due to the superstructure having a big influence on this because of the high weight. Out of the five sub-systems, the floor has the lowest MCI mostly due to the lack of modularity and material choices in this sub-system. Looking at the weight of the five sub-systems that were selected in comparison to the total weight of the vessel, the systems represent a small fraction of 2.62% of the total vessel weight. This does not mean that it is ”useless” to start improving the wheelhouse since lessons learned in the improvement of the wheelhouse can be applied throughout the whole vessel in the end. Recycling is at this moment the most commonly used method to keep materials in the loop. However, recycling should be a last option when looking at the 10R principles and therefore the application of refurbishment, remanufacturing and repurposing should be considered more often. To do this, companies need good contact with their supplier to explore the options of taking back products by the suppliers but also contact with other organisations that can help enable these strategies. Because the floor has the lowest MCI score and there is room for improvement, the floor will be worked out in more detail in the next steps. The low circularity of the floor is a result of the lack of non-virgin materials in the inflow and the low modularity, making it hard to separate materials for recycling/reuse/refurbishment at the outflow. Step four will still look at the life cycle of all five systems with an additional focus on the floor, and step 5 and 6 will only be completed for the floor.

7.4. Step 4: Mapping the system life cycles and associated stakeholders

In this section, step 4 of the framework will be completed where the overall life cycle and associated stakeholders of all 5 sub-systems will be mapped. First, the general life cycle of all five sub-systems will be explained, and then a more in-depth analysis will be made of the life cycle and the stakeholders for the floor.

7.4.1. General life cycles and stakeholders of the five sub-systems

The life cycle of the five presented sub-systems is different. This is because the chair is designed once and then manufactured many times because it is a universal product made by an ”independent” supplier. This is contrary to the superstructure and windows, which are specifically designed for the RSD2513. The consoles and floors are in between the two since they are also used on other vessels but are still quite specifically designed for vessels built by Damen Shipyards. The floors have a standard design but are tailor-made in size for the application on the RSD2513. The Damen RSD2513 tugs are not so-called ”one-off” vessels so this means that there will not be a specific design for every new vessel that is requested but the tugs will be sold multiple times based on the same design.

It can be concluded that the chosen sub-systems can be divided into two categories; Unique products and Multi-user products. A Unique product is identified as a product that is designed specifically for this vessel type and which cannot be used on other vessels, an example being the windows and superstructure. A multi-user product is a product that is usable in multiple vessel types or maybe even other types of systems, an example being the captain’s chair and the floor. These two products have different life cycle because the design and manufacturing process is not the same. Multi-user products can be built in stock whilst unique products are built once the product has been sold. All drafted life cycles are added in Appendix C

The linear material flow of both product types is added in Figure C.1 and Figure C.2. This material flow is the current linear flow without taking the circular economy principles into account. The material flow is visualised from a shipbuilder’s perspective. The colours of the stakeholders show whether it is an internal or external stakeholder. The blue stakeholders are internal and the orange ones are external. These stakeholders are identified quite globally and don’t show a great level of detail. As said before, the most important difference between the two flows is the order of designing, manufacturing and selling the sub-system. A unique product is sold and designed at the same time by use of tenders where there is good collaboration between the sales and design departments of the selling company. The tender is discussed with the client and investors and needs to be designed according to class rules. Only after the product has been sold the detailed engineering takes place and the manufacturing process starts. When looking at a multi-user product, the product is designed with the end user in mind but the client is not involved in the design process. The product is manufactured before it is sold and kept in stock.

There are a few stakeholders that do not play a role when it comes to a specific phase of a sub-system’s lifetime, but they do have an influence on the system. Examples are the government, academies and Non-Governmental Organisations (NGOs). The government can in some cases be the client, for example, when ports that are in the hands of the government need new patrol vessels. The government can also be an investor or be a financial support by giving out subsidies. An example of an NGO that is related to ship design is the Shipbreaking Platform. The Shipbreaking Platform is a global alliance of organisations working to ensure the safe and responsible disposal of end-of-life ships all around the world (NGO Shipbreaking Platform, 2023). Academies mostly provide knowledge to improve the vessels for example by coming up with new design rules or frameworks to improve the circularity of vessels.

The figures show the current situation, but to shift to a circular approach, the flows will also have to shift from linear to circular loops. The circular loops are shown in Figure C.4 and Figure C.3. In this shift, the connection needs to be made between the end-of-life stage and the design stage. This connection is not necessarily a material flow connection but needs to be a knowledge connection. Also, other flows start playing a role. Maintenance is extended with repair, refurbishment and remanufacturing and will loop back to the purchasing and logistics. Decommissioning is extended with recycling and will also loop back to purchasing and logistics. These two looping-back flows are material flows. However, in between decommissioning material from the vessel and looping them back to purchasing and logistics, the recycling process takes place. This is a material flow of its own and is not displayed in the life cycle of the system. In case of repair, refurbishment and remanufacturing arrangements need to be made with the suppliers of the system to see where the responsibility is for these processes. It is convenient for a client such as Damen Shipyards if the suppliers have a take-back process to repair, refurbish and remanufacture their systems. The role of suppliers in a circular material flow can be way more important than in a linear flow. Ideally, the supplier is willing to take back their supplied system at any time so in case of obsolescence of any kind the system can still come to good use. However, this means that a repair, refurbishment, remanufacturing or even recycling process needs to be set up by the supplier. This supplier might in itself also be dependent on suppliers and so on. This means that to get the re-looping cycles in place a new supply chain needs to be set up where decommissioning parties, suppliers, purchasing and logistics and all circularity-enabling companies play a role.

7.4.2. life cycle and stakeholders of the floor

Since the floor was chosen to be the sub-system that will be used for the rest of the framework, it will be reviewed in more depth. As mentioned before, the floor is at this moment produced by Sika. The design process of this floor was done in close collaboration with Damen Shipyards' Research and Development department. The most prominent stakeholders in this process were thus the development departments of both Sika and Damen Shipyards, but also suppliers of the floor were involved to see what the physical options were that met the requirements. The classification bureau that is involved with the RSD2513 design is Bureau Veritas. At this moment, the floor is quite a linear product following the flow that is presented in Figure 7.13 with associated stakeholders.

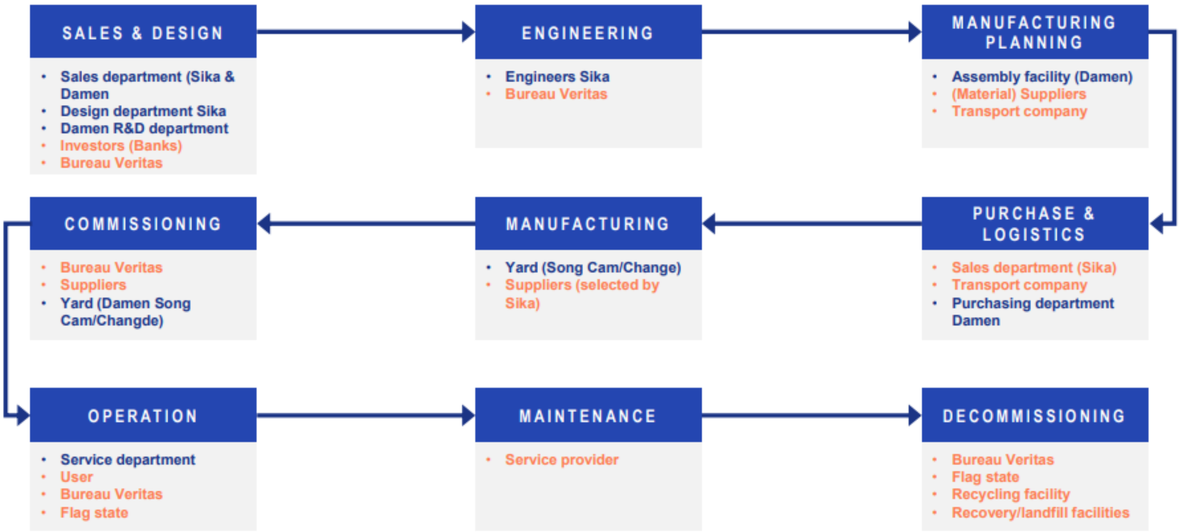


Figure 7.13: The stakeholders specifically for the current floor that is provided by Sika

Sika delivers the materials for the floor and the floor is installed by Damen Shipyards on the yards in Song Cam and Changde. After delivering the vessel, it is up to the client that bought the vessel what to do with the floor during operation, maintenance and decommissioning.

Looking at the shift from a linear to a circular system, changes need to be made and more stakeholders play a part throughout the whole lifetime. This is visualised in Figure C.4. Because it does not matter for the redesign towards a circular product who the supplier is, no further detail will be given.

7.5. Step 5: (Re)designing the system by use of RFLP method, applying circularity principles

Now that all stakeholders have been identified it is time to see what their requirements are and how these requirements translate into functions, these functions into a logical structure and in the end into a physical system. For this step, only the floor will be analysed. It is important to note that the goal is not to design the best floor technically, but the goal is to test the framework and show ways in which circular design strategies can be used for maritime systems.

7.5.1. Requirements

Every stakeholder that was identified in Step 4 has its own requirements. Looking at the stakeholder mappings in step 4, a total of 21 different stakeholders were identified. Out of these 21 stakeholders, seven stakeholders are internal for Damen and the rest are external. As said in the definition of the framework, some of the stakeholders are more important than others. To design a system that reaches the highest possible circularity level, the whole life cycle of the system needs to be taken into account during the design phase. This also means taking into account all stakeholders in the design phase, even though the decommissioning stage might be 30 years in the future. During the design phase, there are three main stakeholders having a say: The design department (of both supplier and client), the client (Damen) and class societies. Where the design department has to implement the requirements of the client and class societies. These three stakeholders will now be listed, including their main requirements. At this moment, little to no stakeholders have demands regarding circularity so first the current, general requirements will be listed.

- Design departments: Meet all requirements of all stakeholders, create a structural and visual good design that is good enough to sell to their customers.
- Damen: Provide a solution to the final customer that is compliant with class but which is also structural, ascetically and economically attractive.
- Class society: Regulations for fire resistance, vibration, and noise reduction.

Every stakeholder has multiple requirements. Some requirements are quite generic, such as minimising cost, while others, such as the noise limit in the wheelhouse, are more specific. The detailed, general requirements are:

- A maximum noise level of 65dB(A) in the wheelhouse (International Maritime Organization, 2012).
- A-60 fire integrity level (Bureau Veritas, 2023).
- Maximum overall frequency weighted R.M.S. vibration level of 3.5 mm/s from 1Hz to 80Hz
- Keeping the height of the floor as low as possible
- Bringing the weight to a minimum
- Have an acceptable delivery time
- Price that is comparable to existing floor systems
- Look aesthetically pleasing
- Strength should be sufficient
- The surface should be smooth, with no bumps or imperfections.
- Lifetime equal to vessel's lifetime

In terms of circularity, requirements should also be set. The goal of redesigning the floor will be to first refuse all materials that are not necessary, bringing the total material use to a minimum. Unfortunately, due to the floor being sized specifically for the wheelhouse of the RSD2513, it will be hard to directly reuse the floor unless a vessel is being refitted or built that has a wheelhouse of similar size. Because the floor has a lifetime that is equal to the vessel's lifetime, with the use of Table 5.1 it can be concluded that repair, refurbishment and remanufacturing should have the highest priority in the design. However, at the end of the approximately 30-year lifetime, repurposing and recycling become of great importance. To every requirement, the principles of the 10R framework can be connected. Therefore the requirements with regard to circularity will be, with the connecting between brackets:

- The system should be able to be disassembled such that all different material types can be separated (R4, R5, R6, R7, R8).
- The so-called top layer should be removable without needing to remove the whole floor to allow for repairs of the top layer (R4).
- The inflow of materials should have as many previously used materials as possible (R0, R1).
- Arrangements should be made to make sure that the parts of the system will be reused after repair or at the end of life (R4, R5, R7).

Looking at the 10R framework, it can be seen that all R-values are represented in a requirement except for R2; redesign. However, the whole purpose of the framework is to reshape a product with a view to the circularity principles, so by carrying out the steps of the framework, also this R-value is paid attention to. The requirements can be visualised in a breakdown structure. This is visualised in Figure 7.14.

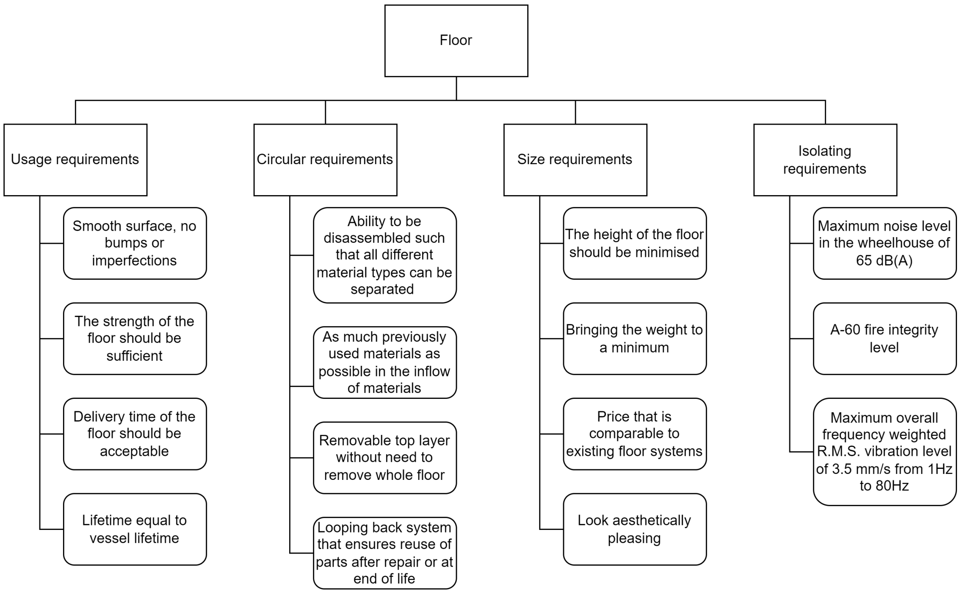


Figure 7.14: Requirement breakdown structure for the floor

Testing the set requirements to the proposed properties of the requirements that Kossiakoff et al. (2011) proposes, it can be concluded that some requirements are not sufficiently defined yet but because some of the requirements will be used only to compare possible solutions to existing solutions, this is not a problem. Also, some of the requirements can be conflicting. A floor that is strong for example might also be heavier, or solutions that allow for disassembly might not meet the fire resistance requirements. Therefore it is important to prioritise the requirements. Requirements by class are the most important because without complying with these requirements, the vessel will not be allowed to sail. Therefore the isolating requirements have the highest priority. After that, the usage and circular requirements should be prioritised. The size requirements are also very important but less important than the others since the focus of this research is on increasing circularity. In the next section, the requirements will be translated into functions.

7.5.2. Functions

The main function of a floor is to be an isolating layer whilst providing a standing surface. The requirements can also be translated into more detailed functions. These functions can again be visualised in a breakdown structure. This is done in Figure 7.15. It can be concluded that quite some requirements cannot be translated to a function, but are more performance and physical requirements. The circular requirements also can be categorised as this type of requirements and are therefore, as already discussed in subsection 6.5.2, not translated into functions.

7.5.3. Logical

In the logical phase, the focus should be on the composition of the system and the connections between the different components and parts. Common sense plays a role here in making logical connections between parts to combine them into components and in the end combine the components into systems. Some of these connections have already been made by categorising the requirements and functions into different subjects. Looking at what physical solutions to combine, the physical solutions will now first be assessed.

7.5.4. Physical

To come from the RFL overview to a physical solution, all possible options have to be considered. As presented, this can be done by use of a morphological chart. The functions have been listed in subsection 7.5.2. For the functions, multiple viable solutions have to be researched. This is done by literature research into materials, shapes, forms and other solution types that can fulfil the set functions. Because it is hard to express circularity in terms of a function, and especially to provide means to assure this, more details are added to the functions. For example, the function of a screw can be to attach two

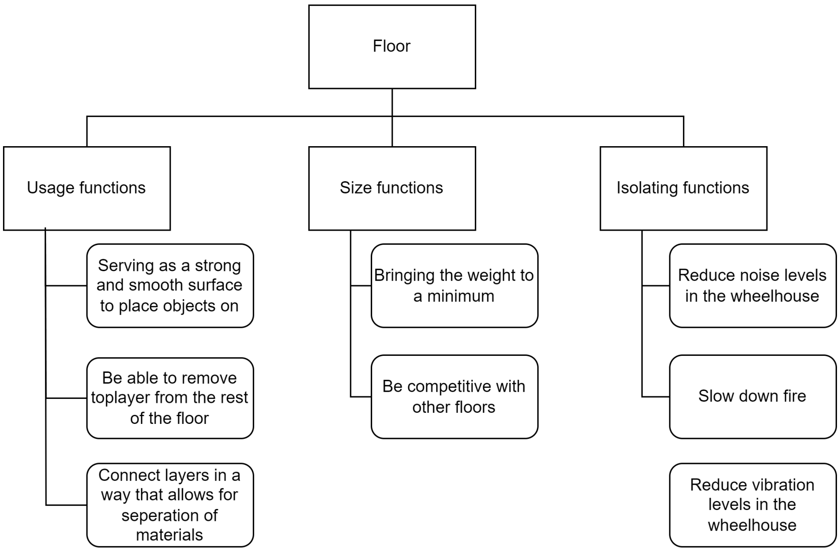


Figure 7.15: Functions breakdown structure for the floor

surfaces to each other, but regarding circularity, this function can be updated to attach two surfaces together with the possibility to detach them at any desired moment. This way, connections such as a glue connection will not be viable options, whilst they do fulfil the practical function. A morphological overview of the solutions linked to the functions is shown in Table 7.7. In the morphological overview, several lines have been drawn that show the best solutions in terms of price, weight, circularity and height. This way, several combinations of options can be explored. However, with the table, single options are explored whilst the final solution might be a combination of multiple solutions as shown in the morphological overview. Also, determining the weight and price of a material is hard based solely on the type of material since for every solution the amount of required material might differ in terms of volume. Therefore an estimation was made to show the potential of the materials.

Table 7.7: Morphological overview of the physical solutions matched with the functions

Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7
Smooth surface	Synthetic cast floor	Carpet	Laminate	Steel plates	Vinyl	PVC	Carbon fibre
Removable top layer	Carpet	Laminate	Vinyl	PVC			
Strong surface	Galvanized steel	Carbon fibre	Aluminium	Cement			
Connecting two layers	Primer	Glue	Welding	Bolds and nuts	Magnets	Rope	Staple
Reduction of noise levels	Isover isolation	Visco-elastic mortar	Self leveling mortar	Stonewool	Cement	Steel plates	
Slowing down fire	Steel plates	Fire resistant glass	Concrete	Fire-retardend treated wool	Iron		
Reduction of vibration levels	Stonewool	Isover isolation	Visco-elastic mortar	Cement	Steel plates		

Cheap
Lightweight
Circular

Let's first look at the inflow of materials. For many of the functions, materials are available that can have a high recycled content or are even reused or remanufactured. For the floor covering, all options except the cast floor can be taken out of the vessel without damaging the materials. This also goes for the solutions matched to the function of providing a strong surface. The steel plates, the insulation, and the lower layers provide the function of reducing noise and vibration levels. Looking at other options to reduce noise more insulation material can be added or cement can be used instead of the steel plates. However, with both options the height of the floor increases, an unwanted result. Looking at the current floor, the main drivers for a low circularity level are the fact that very few previously used materials, parts and components are included in the inflow and the fact that the product is not designed to be taken apart making it impossible to separate materials for repair or recycling at the end of life. An example of this is the ASSY floor covering. The floor covering is purely added to make the floor look nicer and to finish off the floor with an equal layer. However, looking at technical functionality, the top layer is not required. The same goes for the top layer of the floating floor consisting of the Two-component polyurethane cast floor and the Two-component epoxy primer. All objects in the wheelhouse could also be placed on the galvanised steel plates, but this is not done for aesthetic reasons. Following the circular economy principle of refuse, the floor covering and the two top layers of the floating floor can be left out. Now working down the materials from top to bottom, the steel plates could be made of recycled steel, or even, when plates of the right thickness are available, reuse the plates that are available from previous projects. Unfortunately, the bonding adhesive in between the steel plates is made of polyurethane which is not possible to make out of fully recycled material yet. However, the polyurethane can be mechanically removed and mechanically recycled, meaning that it will be changed into flakes, granules or powered and can be used as filling for pillows, toys, etc. (Kemona and Piotrowska, 2020). An alternative for the insulation material can be supplied by Rockwool (n.d.). They have a recycling service to close the loop for stone wool and supply recycled stone wool. The stone wool they offer has a recycled content of 50%. Also, at the end of life, the stone wool can again be repurposed in other isolated locations or be recycled again. The lowest four layers with the primer, VEM and Self-leveling mortar are the most efficient in reducing the noise levels. Due to the use of the Self-leveling mortar, it is hard to separate the layers and they are all not made of a non-virgin inflow. However, this is the lowest layer of the floor and the separation of materials with destruction of the construction could be an acceptable option here. In between the primer layers, there is a VEM, which stands for Visco-Elastic Mortar. This layer has a damping function and technical solutions are available at this moment that can create a VEM out of recycled materials. Next to that below and on top of the VEM there is a layer of primer. Spilman et al. (2017) have conducted research into the use of recycled sources for high-performance coating materials. In this, they conclude that recycled contents of thirty to sixty per cent can be realised depending on the type of coating. All in all, the lower layer might prove to be very efficient in terms of isolating and size functions, but it does not completely fulfil the circular requirements.

After exploring all of the options, a final conclusion can be drawn for the redesign of the floor in the wheelhouse. It can be concluded that even though the lower four layers of the current floor might not be the most circular option for insulation, they are the best solution in terms of functionality and it is not technically possible to find another, more circular solution that still fulfils all functions. However, the primer can be made with a higher recycled content. The isolating layer will be further complemented with recycled insulation material and two steel plates made of recycled content. On top of the steel, many options are possible and the best option might be to let the client buying the vessel choose the surface as long as it is not a cast floor. For recycling purposes, PVC is the best option preferably in the form of planks that can be clicked together. If preferred, a sub-floor can be added but in terms of noise or vibrations, this should not be necessary. A visual of the redesigned floor is shown in Figure 7.16.

However, to ensure a long lifetime and a good purpose for the materials at the end of the floor's life, agreements need to be made between different stakeholders. Agreements such as Rockwool taking back the stone wool for recycling or the supplier of the PVC laminate reusing the laminate again on other vessels.

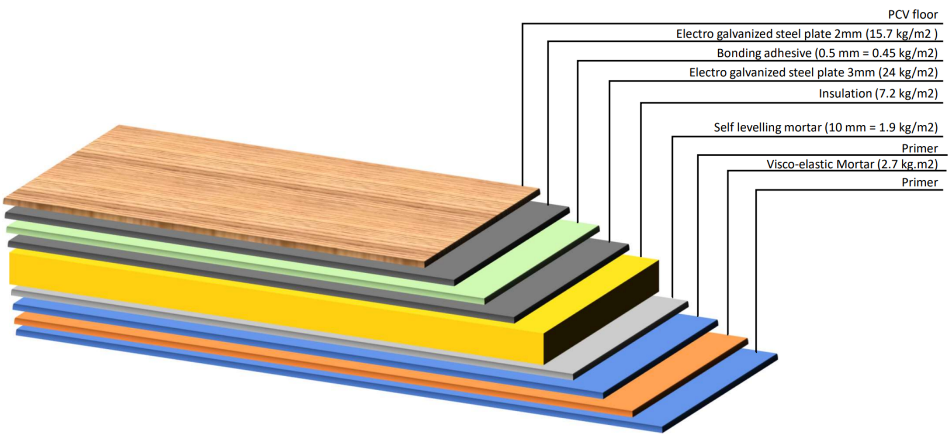


Figure 7.16: Visual of the redesigned floor

The lifetime of the new design is expected to be equal to the lifetime of the vessel; 20 years. In case during the lifetime repairs will need to be carried out, the floor has been specifically designed to be able to do so. The top layers such as the PVC, steel plates and insulation can be replaced without removing the lower layers.

Regarding a business model, a floor is a product that, with the right agreements, can be easy to return to the original manufacturer. However, it will be harder to recover value from the floor. Next to that, the expectation is that the floor will have a low embedded value at the end of life on board the RSD2513 tug. Therefore, looking at Figure 6.14, the best strategy will be "design for recycling" in combination with partnerships. This is exactly what also came out of the rest of the case study and is therefore seen to be the best business model for this new design.

Looking at the cost of the new design, these will very likely be comparable to the cost of the floor supplied by Sika. First of all, compared to the "old" floor, the top layer with the floor covering is left out. Next to that, other layers such as the cast floor are also left out and replaced with other solutions. When agreements with suppliers are made for the repair and/or taking back products at the end of life, an overall lower price might be possible since at the end of life the materials can be "sold" back to the supplier, instead of ending up in a landfill. Next to that, with good maintenance, some parts of the floor can be reused after completing their function on board the RSD2513 tug.

7.5.5. Variation of the RFLP's to look for alternatives

The proposed solution meets the requirements as set by class, the client and the design departments. However, if one of the three main stakeholders would be willing to set less strict requirements or the requirement can be fulfilled by another sub-system, more variation is possible in the design. In this section, three variations on the RFLP structure of a floor inside a wheelhouse will be made. After this, the variations will be compared to the current floor and the redesigned floor on circularity, functionality and cost. The goal of this analysis is to see the influence of the different requirements on the physical solution.

Variation of RFLP structures

Three variations on the floor will be explored and for every variation, the steps of RFLP will be completed. The goal is to design three alternatives for the floor by leaving out requirements, compared to the previous sections. Since this research is about increasing circularity, the circular requirements will not be left out.

Alternative requirements

Now, three different scenarios will be introduced. In these scenarios, compared to the "original" requirements as presented in Figure 7.14, several requirements will be left out. This does not mean these requirements are not there anymore, but they will be completed by other sub-systems as will be explained per scenario. The choice for the alternative scenarios is based on the expectation that these three variations in requirements will have the strongest influence on the physical solution. To see where the biggest influence actually is, the alternative scenarios are:

1. <u>The fire integrity level of the floor is not required.</u> This can be realised by including this requirement in the ceiling of the deck below the wheelhouse. The goal of the requirement is to stop the spreading of the fire from the wheelhouse onto other decks, or the other way around. In case the fire integrity level is included in the ceiling of the deck below, this goal is still fulfilled.
2. <u>The reduction of noise and vibration levels is not a requirement for the floor.</u> This can be realised in multiple ways. First of all by removing the noise and vibration in the first place. The noise and vibration are primarily caused by the engine. In case this engine is replaced with, for example, and electric motor, these noise and vibration levels will decrease significantly. Another solution would once again be to include noise reduction in another sub-system such as the ceiling of the lower deck.
3. <u>There is no requirement to bring the price, weight and height of the floor to a minimum.</u> The current weight and height requirement is based on the reduction of total vessel weight and height, resulting in lower fuel consumption and better stability. However, these outcomes can also be received by other design choices throughout the whole vessel design. Price will be disregarded to look for the best circular solution without having to look at the cost.

For all of the requirements that are left out, the requirements breakdown changes. The requirements as presented in Figure 7.14 are again shown in Figure 7.17 but this time the changes for the alternative scenarios are visualised with crosses. The number next to the cross shows the scenario it relates to.

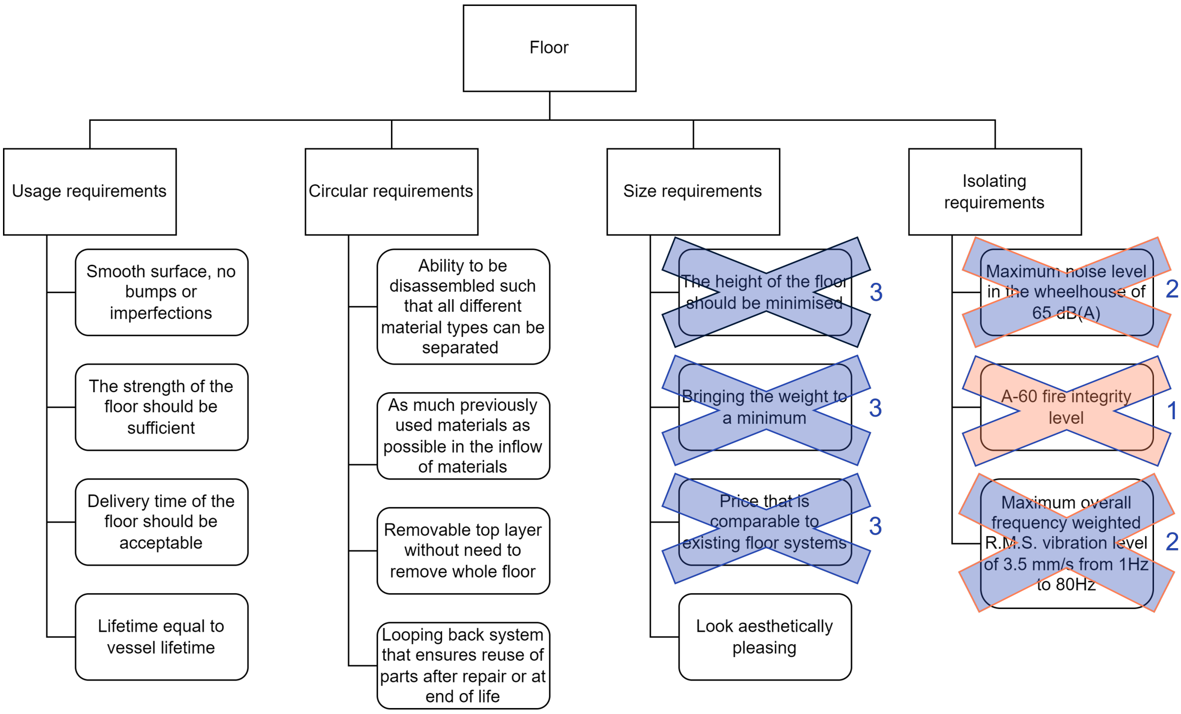


Figure 7.17: The requirements for the different alternative scenarios. The cross number indicates the expired requirement(s) for every scenario.

Alternative functions

A change in requirements directly influences the functions a system has to fulfil. For every scenario, one or two functions can be identified that are related to the requirements and which will also be left out of the design process. The functions that will not be considered, compared to the functions as presented in Figure 7.15, are shown in Figure 7.18.

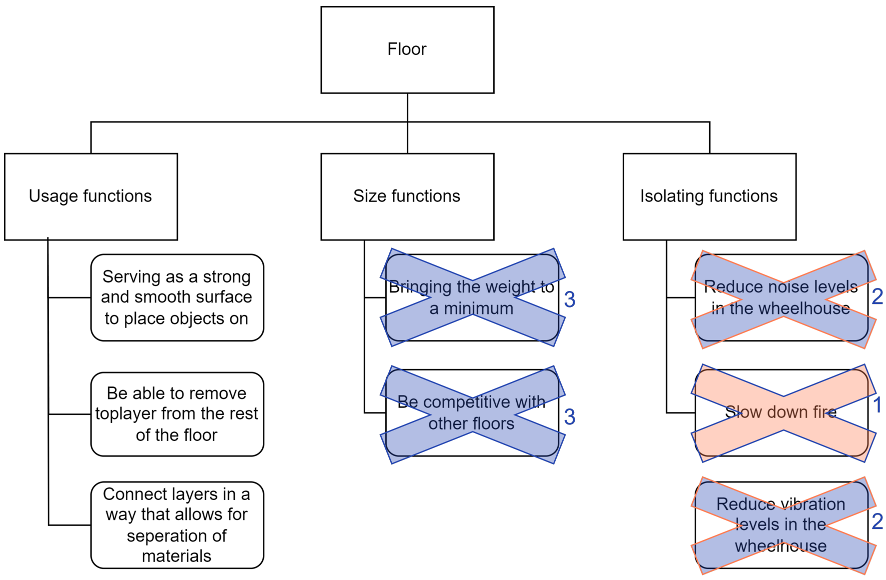


Figure 7.18: The functions for the different alternative scenarios. The cross number indicates the expired function(s) for every scenario.

Alternative logic
Just like in the general case study, it is hard to make logical connections for the sub-system before physical solutions have been explored. Some connections have been made by grouping the requirements and functions in the breakdown. However, the influence on the logical structure is also to be demonstrated later in this section by leaving out some requirements and seeing what influence this has on the physical solution.

Alternative physical solutions
After completing the RFL structure, a physical solution can be found. For the physical solution, another morphological overview can be made. Three separate morphological overviews are made to clearly show the difference in the possibilities. The adjusted morphological overview is shown in Table 7.8. This is the same morphological overviews as shown in Table 7.7 but this time the numbers on the right of the red lines indicate the function(s) that will not have to be considered in the scenario. For every alternative design, the physical solution will now be elaborated upon.

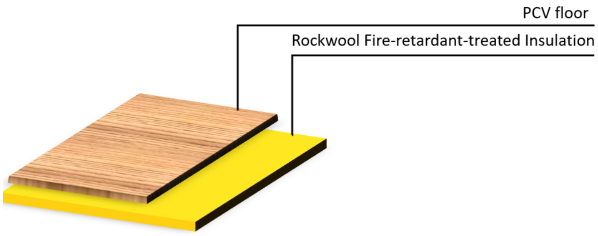
1. The fire integrity level of the "original" floor is a result of the different layers in the floor that are in the first place selected to reduce the noise and vibration levels. Even though the glass wool will have the biggest influence on fire resistance, it is the combination of the whole floor that determines the final result. Therefore, if the fire integrity level does not have to be met, but the noise and vibration requirements remain, it will not change anything about the floor design. It can thus be concluded that in the case the requirement of the A-60 fire integrity level is dropped, the redesigned floor as presented in Figure 7.16 will be the best solution.
2. In case the noise and vibration levels do not have to be reduced by the floor, this means that the main function of the original floor does not need to be fulfilled anymore. The next most important function of the floor in this case is to provide a strong and smooth surface whilst still being compliant with the A-60 fire integrity level. In the original floor, the fire integrity is included in all layers but primarily in the insulation layer. In this case, the layers with a sound and vibration insulating function can be left out. Since the floor is placed on the steel deck, a strong surface is already present. To meet the fire integrity level requirement, a layer of fire-retardant-treated wool will be added. On top of the wool, PVC will be laid to provide a removable top layer and smooth surface. In this alternative scenario, the floor can therefore "simply" consist of a layer of fire-retardant-treated wool and PVC placed on top of the steel deck.
3. The weight and height requirements are used in the selection of the best physical solutions. Because these were the only selection topics next to circularity, without these the "simply" most circular solution can be selected that still fulfils the other requirements. This means that a combination of steel plates and recycled insulation material will be used to create the basis of the floor. On top of this, PVC will be placed to make a smooth and removable surface.

Table 7.8: Morphological overviews for the different alternative designs, the number on the right indicates the function(s) that will not have to be fulfilled per scenario

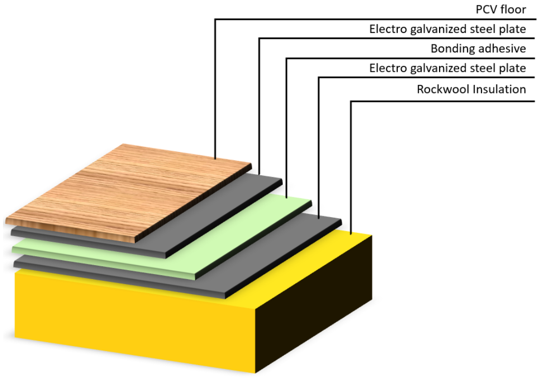
Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	
Smooth surface	Synthetic cast floor	Carpet	Laminate	Steel plates	Vinyl	PVC	Carbon fibre	
Removable top layer	Carpet	Laminate	Vinyl	PVC				
Strong surface	Galvanized steel	Carbon fibre	Aluminium	Cement				
Connecting two layers	Primer	Glue	Welding	Bolds and nuts	Magnets	Rope	Staple	
Reduction of noise levels	Glass wool	Visco-elastic mortar	Self leveling mortar	Stonewool	Cement	Steel plates		2
Slowing down fire	Steel plates	Fire resistant glass	Concrete	Fire-retardend treated wool	Iron			1
Reduction of vibration levels	Stonewool	Glass wool	Visco-elastic mortar	Cement	Steel plates			2

Best price 3
Best weight 3
Most circular

Just like the previous redesign, the three alternative physcial solutions can also be visualised. Since the solution for scenario 1 is the same as the redesign as presented in Figure 7.16, this visual will not be shown again. The other two solutions for alternative scenarios 2 and 3 are visualised in Figure 7.19a and Figure 7.19b.



(a) Visual for alternative scenario 2



(b) Visual for alternative scenario 3

Figure 7.19: Visuals of the physical solutions of the floor based on the requirements in alternative scenarios 2 and 3

Comparing the designs

All of the designs can now be compared on their circularity, functionality and cost. This way, all stakeholders can see the design focus but also make trade-offs on the three subjects. Of course, more topics can be selected to make trade-offs such as weight or delivery time, but for now, these three are selected since the current focus for designers is on function and costs, often referred to as price/quality. By adding circularity, the impact of including this requirement can be seen on the function and cost.

The comparison is shown in Table 7.9. Every design is rated in stars where five stars is the maximum. It can be seen that the column with the circularity has the biggest variation in scores. Even though the circularity of the redesign and alternative 1 are high, about 90 per cent, alternatives 2 and 3 score even better because they use fewer materials, looking at weight. All designs fulfil the functions that were set before starting the design. However, looking at the total amount of stars, it can be concluded that the Sika floor was designed with a focus on function, whilst for the other designs the focus was more on circularity and cost. It is however hard to compare the designs on function because the functions for the alternative designs are not the same as for the Sika floor and the redesign as done in Figure 7.16. The cost of the designs is quite similar except for the design of alternative 2, where way fewer materials were used, resulting in lower cost.

Looking at the influence of requirements on the design, it can be concluded that there is a big difference between the influence of the requirements on the design. The requirement to reduce the noise and vibration levels has by far the biggest influence. Since it is a requirement also by class to have a maximum noise and vibration level in the wheelhouse, this is not a requirement that is likely to be dropped, but one that might change with the ongoing developments regarding alternative propulsion options. To increase circularity, it could be seen that giving in on weight and cost can contribute in a positive way.

The goal of this analysis was to see the influence of the different requirements on the physcial solution. However, since the general function of a floor is to provide a horizontal, smooth and strong surface, this function cannot be fulfilled by any other sub-system than a floor. As a result of this, the design will always be quite similar, whilst if a system would be analysed that should, for example, provide a waterproof cover, there are many sub-systems that can fulfil such as purpose; options would be a roof, an umbrella, a rain-jacket, etc. So it depends a lot on the function that is being selected and how much space there is for alternative physical solutions. Next to that, the physical solution is very dependent on the preferences of the eventual owner of the (sub-)system. In case the client prioritises circularity, this will also be high on the agenda of the designer.

A final point to be made here is that the measurement of the different requirements varies, also making it harder for clients to get a feeling for certain requirements. For example, the measuring of the noise level in the wheelhouse is straightforward and nobody will doubt the results, but for the measuring of circularity a lot of factors play a role and a lot of ways of measuring are available. This makes it harder to set requirements for a client and compare the results of different design proposals.

Table 7.9: Comparison of the designs on circularity, function and cost

	Circularity	Function	Cost
Sika floor	★	★★★★★	★★★
Redesign	★★★	★★★★	★★★
Alternative 1	★★★	★★★★	★★★
Alternative 2	★★★★★	★★★★★	★★★★★
Alternative 3	★★★★	★★★★★	★★

7.6. Step 6: Validating the (re)design

As a final step of the framework, the redesign as presented in Figure 7.16 will be tested to the set requirements and functions, but will also be tested on the new circularity level. After this, it can be concluded whether or not the proposed solution is an improvement compared to the existing system.

7.6.1. Validation Matrix

On the next page, in section 7.7, the PMM is filled out for the redesigned floor. It can be seen that all requirements are matched to functions and the other way around. Additionally, all requirements and functions are translated into physical solutions. Therefore it can be concluded that, in terms of requirements and functions, the redesign is a viable replacement of the current design. However, for some requirements, there is only a weak relationship matched to a function or physical solution. So in case a new design is made, these requirements are where improvements can be made.

7.6.2. Measuring circularity

To further validate the design, once again, the circularity of the system will be measured. To compare the "old" floor and the redesigned floor, the circularity level of the Sika floor will also be calculated at the same level of detail as the new floor is built up. It can be seen that with the higher level of detail, the circularity of the Sika floor has increased a bit. However, comparing it to the new floor, the redesign shows a way higher circularity outcome. The table with the calculation is shown in Table 7.10.

The biggest difference can be spotted in the outflow of the materials. For the "old" floor, there is no potential to win back materials due to the construction of the floor, but also due to the lack of agreements between stakeholders. For the redesign, all stakeholders will have to be on board to be able to keep the parts and materials in the circular loop. This means that with every supplier, agreements have to be made for taking back materials, or a separate stakeholder needs to be found that will reuse the materials. Next to that, agreements have to be made with the owner of the vessel to actually use the supplier agreements to keep the materials in the loop.

Table 7.10: Comparison in MCI level of the "old" and "new" floor design

System	Parts	Mass	Inflow				Outflow					MCI	
		Mass [kg]	Virgin	Recycled	Refurbished	Remanufactured	Refurbishment	Remanufacturing	Repurposing	Recycling	Recovery	MCI	Total MCI
Redesigned floor	PVC laminate	63,84	0,00%	100,00%	0,00%	0,00%	100,00%	0,00%	0,00%	0,00%	0,00%	1	0,905
	Steel plate	125,286	0,00%	100,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,00%	0,00%	1	
	Bonding adhesive	3,591	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,5	
	Steel plate	191,52	0,00%	100,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,00%	0,00%	1	
	Insulation	57,456	50,00%	50,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,00%	0,75	
	Self leveling mortar	15,162	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,5	
	Primer	0,1	70,00%	30,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,65	
	Visco elastic mortar	21,546	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Primer	0,1	70,00%	30,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,65	
Original floor	Two-component seal layer	1,1172	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	0,149
	Coating, Coloured chips	0,399	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Two-component seal layer	1,1172	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Two-component decorative resin	19,152	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Synthetic floor covering	0,27132	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Two-component polyurethane cast floor	16,758	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Two-component epoxy primer	0,1	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Steel plate	125,286	62,50%	37,50%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,1875	
	Bonding adhesive	3,591	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Steel plate	191,52	62,50%	37,50%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,1875	
	Steel strip	57,456	62,50%	37,50%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,1875	
	Insulation	18,8328	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Self leveling mortar	15,162	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Primer	0,1	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Visco Elastic Mortar	21,546	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	
	Primer	0,1	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0	

7.7. Review of the framework

All in all, it can be concluded that the framework can be used to review a system and identify sub-systems, components and parts. To do so, a lot of information is required from suppliers by asking questions that suppliers might not have been asked before. Therefore it might be useful to first use the framework at the equipment manufacturing companies instead of at the company that is integrating the systems. The fact that many suppliers have not been asked before to look at their inflow and outflow of materials shows that there is a need for a framework like this to give the incentive for companies to start looking at their impact with regard to circularity. Next to that, for a lot of sub-systems in the wheelhouse, there is a bigger potential in terms of recovery than at this moment established. Consoles could be remanufactured or refurbished, but at this moment that is not common practice. Looking at the process of redesigning a system, it became clear that a great level of detail is required to come to a more circular design. This requires very specific knowledge of materials and the system that is being reviewed. This knowledge often goes beyond the expertise of a ship designer and therefore the redesign of a specific sub-system or component might be more suited to be performed by the equipment manufacturer. During the case study, it became clear that the use of the framework is a time-consuming process due to the lack of good information to fill out the framework. Next to that, this case study focused only on a few sub-systems in the wheelhouse, whilst when a whole vessel has to be designed, this will be a more time-consuming process, with more stakeholders and more agreements to be made. Also from this point of view, it is important that stakeholders assess their own process on the topic of circularity to make of designing circular vessels possible for the design and shipbuilding companies.

To show the distribution of the time that was used to perform the case study, an effort summary has been added in section D.2. From this, it turns out that most time was spent on gathering information and especially information that was not available through the supplier which resulted in the use of a database with industry averages. To complete the framework, contact should be made with more stakeholders such as physical solution suppliers to see what the complete market has to offer and to make a good, deliberate choice in terms of materials, modularity, cost and reliability.

Table 7.11: Filled in Product Management Map for the redesigned floor

(● = filled dot, ○ = open dot, ◉ = grey dot)

		Functions								Physical solution			
		Serving as a strong and smooth surface to place objects on	Be able to remove toplayer from the rest of the floor	Connect layers in a way that allows for separation of materials	Bringing the weight to a minimum	Be competitive with other floors	Reduce noise levels in the wheelhouse	Slow down fire	Reduce vibration levels in the wheelhouse	Combination of Primer, VEM and Self leveling mortar	Isolation wool	Steel plates with bonding adhesive	PVC floor covering
Requirements	Smooth surface, no bumps or imperfections	●	○	○			○					◉	●
	The strength of the floor should be sufficient	●	◉		○		○	○	○			●	
	Delivery time of the floor should be acceptable					○				○	○	○	○
	Lifetime equal to vessel lifetime	○	○	○						○	○	○	○
	Ability to be disassembled such that all different material types can be separated		◉	●	○	○	○			○	●	○	●
	As much previously used materials as possible in the inflow of materials				○	○				○	●	◉	●
	Removable top layer without need to remove whole floor	○	●	○		○						◉	●
	Looping back system that ensures reuse of parts after repair or at end of life		○		◉	○					●	◉	◉
	The height of the floor should be minimised				○	○	○	○	○	◉	◉	◉	◉
	Bringing the weight to a minimum				●					◉	○	◉	◉
	Price that is comparable to existing floor systems		○			●				◉	◉	◉	◉
	Look aesthetically pleasing	◉				○				○	○	○	●
	Maximum noise level in the wheelhouse of 65 dB(A)						●		○	●	●	●	
	A-60 fire integrity level							●			◉	●	
	Maximum overall frequency weighted R.M.S. vibration of 3.5 mm/s from 1Hz to 80Hz						◉		●	●	●	●	
Physical solution	Combination of Primer, VEM and Self leveling mortar				○	○	●	○	●				
	Isolation wool		◉	◉	◉	○	●	◉	◉	C,S			
	Steel plates with bonding adhesive	●	●	○	○	○	●	◉	●	S	C,S		
	PVC floor covering	●	●	●	○	◉				S	S	C,S	

8 Discussion

For this research, the goal was to answer the main research question:

How can circularity be taken into account in the ship design process by linking product characteristics to circularity indicators?

To investigate the answer possibilities, the definition of circularity, a way to measure circularity, circular design methods and ship design methods were first reviewed. As a final answer, a framework has been drafted to take circularity into account during the ship design process combining all the principles and frameworks that were found before.

8.1. Scope effects

In the scope of this research, it was already determined that the focus of this research would only be on circularity, leaving out all factors that play a role in the topic of sustainability. Sustainability is a combination of Environmental, Social and Governance elements. To take all of the environmental effects of a system into account, it would be better to perform a Life Cycle Analysis in combination with a circularity assessment evaluating the whole life cycle of the system; from (raw) material extraction to recycling efficiencies. Trade-offs might have to be made in that case to give a value to circularity to be able to compare it to for example CO_2 emissions.

8.2. Limitations

This framework has been tested using a case study where the wheelhouse of an RSD2513 was subjected to the framework. It turns out that the framework has multiple limitations:

- The analysis/optimisation only looks at the inflow and outflow of materials in the end product, not at the materials used during the production or dismantling process, nor does it look at recycling efficiencies.
- The MCI calculation is based on weight, whilst hazardous and rare materials should also be considered an essential factor during the design phase.
- It is hard to compare a system's lifetime and use frequency to industry averages because the systems that are analysed set the average.
- The level of detail of the framework is highly dependent on the information available from suppliers, often resulting in an estimation based on industry averages with general weights.
- The use of industry averages is not a representative way of calculating the circularity level of a product.

Looking at all these limitations, it can be concluded that the provided framework is a concrete step in the right direction but further extensions can be made to solve these limitations. With the help of all suppliers the framework can be a good guide for furture designers but steps are required which will be elaborated upon now.

8.3. Roadmap to implementation

To actually implement and use the framework, steps are required. A visual of the required steps is added in Figure 8.1. First of all, everybody involved in the framework has to be on the same page regarding the definition of circularity. As concluded in chapter 3, many companies and individuals use their own framework for the definition of circularity. With the upcoming ISO standard, this might change but it is important to inform the stakeholders in the system lifetime about the definition of circularity used during the design phase so the correct steps to keep this circularity level as high as possible to the at all times. Contact with suppliers during the case study showed that some see renewable materials as a circular option whilst others only see actually reused material as circular.

The same goes for the method of measuring circularity; companies or individuals that wish to collaborate on the topic of circularity have to have the same method of measuring so they are talking about the same numbers and are able to compare different options. Again the ISO standard might help here but the new rules for reporting on circularity can also provide some guidance here.

Once everybody is on the same page about the definition and way of measuring, information needs to be gathered about the current situation to set a baseline and monitor improvement. To do this, every stakeholder that is involved in determining the content of the system should evaluate their influence on the material used. Starting with the material extraction and ending with the final product going to the recycling facility. This means that, for example, for the steel for the superstructure, the steel manufacturer needs to review its process to get information about the amount of recycled content that goes into new steel, but also evaluate what the losses are when cutting plates. In this process, communication between all the stakeholders is key in order for designers to make the correct design choices in the end. Next to that, it is important to specify the materials used in systems in more detail. Currently, the bill of material mentions plastic or composite, but to assess circularity, more detail on the type of plastic or composite is required since it makes a difference in the repairability and recyclability of a system. During the assessment of circularity at the supplier level, it is important to directly note and write down these details.

Once the current situation is mapped and all stakeholders have an idea about their impact in terms of circularity, the framework can be used to improve or renew designs. As said before, the most important focus point during the design process is breaking down the system to identify its function and designing a circular solution to fulfil this function, instead of trying to improve a current design whilst this might not be the optimal solution when looking at circularity. For designers to know what to focus on in terms of circularity, it would be wise for companies trying to include circularity to have KPIs on the topic to provide a guideline. If that is not the case, designers should set circular requirements based on client demands or even their own vision. Since, in the ideal case, all stakeholders have already mapped their progress in terms of circularity, designers can now optimise their design based on all requirements, functions and logical structures set based on the needs in terms of general and circular demands.

For all this to work, incentives should be there for designers such as the design department of Damen Shipyards to start designing vessels with circularity in mind. Incentives can be government requirements or rules, but also clients asking for this. Additionally, the new CSR reporting requirements will help to give a push in the right direction for companies to start thinking about their circularity. Looking at the current status of circularity in the maritime sector, it will take years to complete the steps of this roadmap. Based on the suppliers that were asked about their efforts to include circularity, circularity will most likely not be a main focus point as long as it is not obligatory by regulations. With the new CSRD reporting regulations, companies will have to start reporting on their in and outflow of materials, creating an opportunity to also start with assessing products in more detail. However, many suppliers sell a lot of different products and it will cost them time and resources to complete circularity assessments. The cost of this time and resources will probably influence the price of the final products of the supplier, resulting in more expensive products at first. However, the total cost of ownership of circular products will (most likely) be lower than the TCO of a ”normal” product.

Lastly, during several talks during this research, the conclusion could be drawn that many individuals in the maritime sector are conservative and hesitant to use previously used systems, components, parts or materials due to the perception that these are unreliable, have lower performance and are more expensive, whilst this is not true. A remanufactured system should perform as good as a new system and will most likely even be cheaper and faster deliverable. To overcome these unfounded arguments, information should be provided about the definition and possibilities of circularity to all parties involved but also teaching about this in an educational context can help change the minds of future engineers.

Once again, in these types of uncertainties, a standard such as the one being drafted by the ISO can help. In case products or companies are ISO-certified, this can be used as a way to control the quality of suppliers and their products.

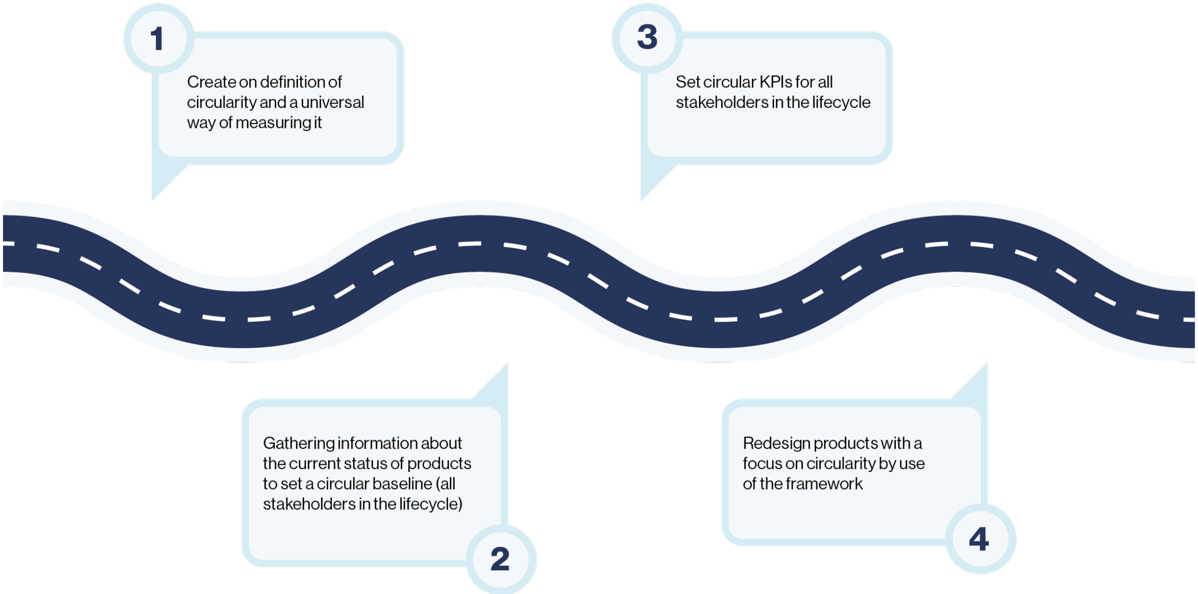


Figure 8.1: Visual of the roadmap to implementation

8.4. Recommendations

To continue research on the topic of circular ship design, multiple recommendations are formulated:

- When performing an analysis of the environmental impact of a system, often only the CO_2 emissions are taken into account. It would be preferable to have a method that performs a life cycle analysis that takes both the "general" environmental impact and the circularity of the system into account. This way, trade-offs can be made between different systems whilst having a complete image of the possibilities.
- At this moment, circularity does not have a value that is expressible in a number. This results in companies having a conservative view towards circularity, often assuming it is more expensive than systems that follow a linear lifetime. Therefore it would be wise to perform a study into the reduction of the environmental impact a fully circular product makes, but also review the reduction or increase of the cost and lead time of a circular product and compare this to a non-circular product.
- The goal of a shipbuilding company such as Damen Shipyards can be to become 100% circular, but the process to get there involves many stakeholders. To start with implementing more circular components in the end product, a start could be to perform research similar to this research at an equipment manufacturer to see the more practical potential and also have the potential to change the business model of this manufacturer towards one where used products are taken back and directly reused in the production process to (re)new(ed) products.
- To help organise the available information on a system with regard to circularity, it would be helpful to set up an (international) system that captures all relevant information in a document. This document could then be used during the lifetime and at the end of the life of a system to see the potential of all materials used in the system. This way, a client will also be able to compare products on their circularity level.

9 Conclusion

In this research, a method was created to include circularity in the ship design process. The main research question that is answered in this thesis is:

How can circularity be taken into account in the ship design process by linking product characteristics to circularity indicators?

In order to systematically answer the main research question, six sub-questions were formulated. Through answering these sub-questions, the context of the problem was analysed and the research was guided in the direction of answering the main question. The answers to these questions are found in consecutive order in chapter 3 to chapter 7. A summary of the conclusion for every sub-question is presented here.

1. To what extent and in which way is circularity at this moment present in the shipbuilding industry?
At this moment, the circular economy principles are mostly present during the operational phase of shipping; repair is common practice. Ship Recycling is also common practice but this happens in countries such as Bangladesh, India and Pakistan where strict environmental regulations are absent. Also, there is little information from these countries about the destination of the products/materials that are taken from the vessels. This all shows that the current focus is mostly on the principles of reuse, repair and recycling, whilst other circular economy principles also have the potential to be included. Quite some regulations are put into place regarding circularity, making companies more and more aware of the importance of the circular economy principles. One of the regulations is the Hong Kong Convention but this is not signed yet by enough flag states to put it into practice; showing that not all countries are willing to put effort into enforcing it, most likely due to the cost of the extra work. During the design stage, circularity is not yet a topic that is often considered and materials with the best price/quality rate are chosen instead of remanufactured products or recycled materials. To make a fully circular vessel, all stakeholders during the lifetime of the vessel should be considered during the design phase, making reuse and repair but also end-of-life potentials things that are already thought through during the design phase. The design phase is very important in the step to a circular economy because during this phase 80% of a product's environmental impact is already determined.

2. How to achieve circularity?
The main takeaway for every circular framework is to have as little waste as possible and ideally never throw any materials away. This can be done by both slowing down and closing resource loops to make sure products maintain their added value for as long as possible and minimise waste. However, because the concept of circularity is relatively vague and amorphous, most companies are moulding and defining circularity in ways that are most relevant to their core business. Many frameworks are available on the market but for this research, the 10R framework was chosen. The 10R framework prioritises different value retention methods from design until the end of life. This framework was chosen because it shows clear steps for the circularity level of a product/material in every stage of the life cycle

of the product; from design until the end of life (in its current function). Additionally, even though R1 until R8 can all be seen as circular, it is important to make a clear distinction between the levels of circularity, something that other frameworks have a less clear definition of.

As well as for the definition of circularity, there also exist multiple frameworks on how to measure the circularity of a product/material. The main takeaway of every method is measuring the amount of circular inflow and circular outflow in a percentage and taking the average of this. To measure the circularity during the research, the Material Circularity Indicator is chosen because it makes a clear distinction between the different circularity levels of the 10R method, the formulas are clear and open access, and the focus is on the product level.

3. What is the best design approach to address circularity in ship design?
To combine the topics of circularity and ship design, the current practices for both should be reviewed. As stated before, regarding circularity the 10R framework is used. With this framework, ten value-retaining steps are ranked in order of importance and biggest influence on circularity. Every R-value is supported by a design focus and sometimes even multiple. However, the design approaches have a focus on consumer goods and are not yet applied in ship design approaches.

Ship design approaches can be divided into four classes of high-level design strategies. Out of these four, systems engineering is chosen as the best design approach since it defines the customer needs and required functionality early in the development cycle, focuses on documenting requirements and after that proceeds with design synthesis and system validation while considering the complete problem. These are all important characteristics when looking at circularity since for circularity the whole life cycle needs to be considered from the start.

The biggest difference between the ship design approach and the circular design approaches is the need for a clear and structured design method for ship design, which is less important for consumer goods. Next to that, consumer goods are influenced by fashion and are often mass-produced. To combine the two, the circular design principles will be included in the steps of systems engineering because systems engineering follows a clear step-by-step approach.

4. How do key indicators influence the circularity level of a system?
In total, six key indicators have been identified; lifespan, use frequency, cost, modularity, material choice and reliability. Lifespan and use frequency are indicators that can help to prioritise the different circular design strategies. Cost plays an important role during the lifetime and at the end of life together with modularity, material choice and reliability. They determine the willingness of a product owner to repair a product or reuse it, compared to repurposing or recycling it. For every key indicator, practical design principles can be addressed for the different stages of the life cycle.

5. What is the impact of including circularity in the ship design approach?
To include the principles of a circular economy into the ship design process, the design process needs to start from the beginning. This process starts with a needs analysis and then gathers all requirements and functions the (re)new(ed) system should comply with. It is important to start from the beginning because adjusting a current design might not prove efficient in terms of circularity. The first R-value of ”refuse” will never be met if the need for a system is not considered and proven first. To prove the need for a (re)new(ed) system, current systems can be analysed. For this, a lot of contact with suppliers is needed, asking for information that they might not have been asked for before. Examples of information that is needed from the equipment supplier are the origin of the inflow of materials and the exact composition of the system. A lack of this information is posing a challenge in assessing the products that are available on the market. Another important aspect of the process is to map the circular life cycle of the product and link all stakeholders to the cycle. These stakeholders play a bigger role than in products that are designed for a linear economy, making them essential in more steps of the life cycle. Finally, it is important to design with a strong focus on circularity whilst taking the whole life cycle into account and in the end validate the design by checking with the requirements and functions that were set beforehand.

6. How to improve the level of circularity in a wheelhouse?
By applying the framework to (re)design the wheelhouse of an RSD2513, the framework was tested. In this wheelhouse, five sub-systems are analysed at first; the captain’s chair, the consoles, the windows,

the superstructure and the floors. Eventually, the floor was completely analysed based on the results of the circularity calculation. First of all, it can be concluded that gathering information to complete the framework is a big struggle. Many suppliers have not been asked before about the in and outflow of their products nor looked into detail about material choice or modularity. Next to that, for a lot of sub-systems in the wheelhouse, there is a bigger potential in terms of recovery than at this moment established. Consoles could be remanufactured or refurbished but, at the time of this research, that is not common practice. Looking specifically at the floor, a redesign has been made based on the RFLP method which increased circularity 15% to 91%. Important to note here is that with the redesign also agreements with suppliers will have to be made to ensure that materials stay in the circular loop. Looking at the process of redesigning a system, it became clear that a great level of detail is required to come to a more circular design. This requires very specific knowledge of the materials of the system that is being reviewed. This knowledge often goes beyond the expertise of a ship designer and therefore the redesign of a specific sub-system or component might be more suited to be performed by the equipment manufacturer.

Main research question:
How can circularity be taken into account in the ship design process by linking product characteristics to circularity indicators?

To include circularity in the ship design process multiple principles and frameworks were combined. First of all, for the definition and ranking of circularity, the 10R framework was deemed the most appropriate, in combination with the adjusted MCI method for the calculation of the circularity level. With the 10R framework also come 10 design strategies for consumer goods that have been compared to the ship design approach of systems engineering. As a last theoretical step, key indicators were identified that influence the circularity of a system. After all this, the 10R framework for the definition of circularity, the corresponding circular design strategies, the method of systems engineering, and several key indicators were combined into a framework that represents a step-by-step guide on how to design a circular system. The main purpose of the framework is to prove there is a valid need for a (re)new(ed) system and starting at the beginning with the design process is to fully focus on a system's function instead of trying to improve an existing system that might not be the optimal solution for the function it needs to fulfil. To make the framework work, contact with the suppliers is a very important aspect since the information required to fill out the steps has to come from them. Next to that, changes to make products more circular will also require suppliers to change with regard to design and be more involved during the whole life cycle of a system to ensure that materials are kept in the circular loop.

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A

Appendix to chapter 3: The 12 principles of green engineering

The 12 Principles of Green Engineering

Principle 1	Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.
Principle 2	It is better to prevent waste than to treat or clean up waste after it is formed.
Principle 3	Separation and purification operations should be designed to minimize energy consumption and materials use.
Principle 4	Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
Principle 5	Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
Principle 6	Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
Principle 7	Targeted durability, not immortality, should be a design goal.
Principle 8	Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
Principle 9	Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
Principle 10	Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
Principle 11	Products, processes, and systems should be designed for performance in a commercial "afterlife".
Principle 12	Material and energy inputs should be renewable rather than depleting.

Figure A.1: The 12 Principles of Green Engineering (McDonough et al., 2003)

B

Appendix to chapter 4

This appendix is divided into two sections. In the first section, an overview of all circular design methods present in the literature is displayed. In the second section, a more detailed description is given of the theory of ”design for preserving product integrity” as presented by den Hollander (2018).

B.1. Taxonomy of design methods

Table B.1: Taxonomy of DfX strategies based on Moreno et al. (2016)

DfX Approach	Circular Design Strategy	Design Focus	DfX Method/Tool	Literature Sources
Design for resource conservation	Design for circular supplies	Design for closing resource loops	Design for biodegradability	Bocken et al. (2016), McDonough and Braungart (2002)
			Design with healthy/smart processes/materials	Bocken et al. (2016), McDonough and Braungart (2002), Hargroves and Smith (2006)
	Design for resource conservation	Design for reduce resource consumption	Design for production quality control	Boothroyd (1994), Allwood and Cullen (2012)
			Design for reduction of production steps	Allwood and Cullen (2012), Vezzoli and Manzini (2008)
			Design for light weighting, miniaturising	Allwood et al. (2011), Vezzoli and Manzini (2008)
			Design for elimination yield loses/ material/resources/parts/packaging	Allwood and Cullen (2012), Vezzoli and Manzini (2008)
			Design for reducing material/resource use	Ashby and Johnson (2003), Allwood et al. (2011), Allwood and Cullen (2012), Clark et al. (2009), Vezzoli and Manzini (2008) Cramer (2022), Reike et al. (2022)
Design for slowing resource loops	Design for long life use of products	Design for reliability and durability	Design on demand or on availability	Bhamra and Lofthouse (2008), Chapman (2015), Clark et al. (2009), Vezzoli and Manzini (2008)
			Design the appropriate lifespan of products/components	C. A. Bakker et al. (2010), C. Bakker, Wang, et al. (2014), Bhamra and Lofthouse (2008), Bocken et al. (2016), Chapman (2015), Clark et al. (2009), Cooper (2000), Lofthouse (2006), van Nes and Cramer (2006), den Hollander (2018)
		Design for product attachment and trust	Create timeless aesthetics	C. A. Bakker et al. (2010), C. Bakker, den Hollander, et al. (2014), den Hollander (2018) Bhamra and Lofthouse (2008), Bocken et al. (2016), Chapman (2015), Lofthouse (2006)
			Design for pleasurable experiences	Bhamra and Lofthouse (2008), Bocken et al. (2016), Chapman (2015), Lofthouse (2006)
			Meaningful design	Bhamra and Lofthouse (2008), Bocken et al. (2016), Chapman (2015), Clark et al. (2009), Lofthouse (2006), den Hollander (2018)
		Design for extending product life	Design for repair/refurbishment	C. Bakker, Wang, et al. (2014), C. Bakker, den Hollander, et al. (2014), Bocken et al. (2016), Chapman (2015), Kimura et al. (2001), van Nes and Cramer (2006), Stahel (2016), Sumter et al. (2018) Reike et al. (2022), den Hollander (2018)
			Design for easy maintenance, reuse and repair	C. Bakker, Wang, et al. (2014), Bocken et al. (2016), Bogue (2007), Chapman (2015), Johansson (2008), Edwards (2002), van Nes and Cramer (2006), den Hollander (2018)
			Design for upgradability and flexibility	C. Bakker, Wang, et al. (2014), Bocken et al. (2016), Bogue (2007), Chapman (2015), Johansson (2008), Edwards (2002), van Nes and Cramer (2006), den Hollander (2018)
		Design for dematerialising products	Design for product-service systems	C. Bakker, den Hollander, et al. (2014), Clark et al. (2009), Morelli (2006), Sundin and Lindahl (2008), Tukker (2015), Vezzoli and Manzini (2008)
			Design for swapping, renting and sharing	C. Bakker, den Hollander, et al. (2014), RSA (2013), Tukker (2015)
	Deign for multiple cycles	Design for recovery	Design for easy end-of-life cleaning, collection and transportation of recovered material/resources	Vezzoli and Manzini (2008)
			Design for cascade use	Accorsi et al. (2015), Vezzoli and Manzini (2008)
			Design for (re)manufacturing and dis- and re-assembly	C. Bakker, den Hollander, et al. (2014), Bocken et al. (2016), Bogue (2007), Chapman (2015), Edwards (2002), Hatcher et al. (2011), Johansson (2008), Kimura et al. (2001), Sundin and Lindahl (2008), van Nes and Cramer (2006), King et al. (2006), Reike et al. (2022), den Hollander (2018)
			Design for upcycling/recycling	King et al. (2006), Vezzoli and Manzini (2008), Moreno et al. (2016), H&M Group (2021), Veelaert et al. (2017)
Whole Systems Design	Design for systems change	Design to reduce environmental backpacks	Design for the entire value chain	Charnley et al. (2011), Chertow and Ehrenfeld (2012), Claypool et al. (2014), Vezzoli and Manzini (2008), Wells and Seitz (2005)
			Design for local value chains	Wells and Seitz (2005), Vezzoli and Manzini (2008)
		Design for regenerative systems	Design for biomimicry	Nagel et al. (2010), Schenkel et al. (2015), Vincent et al. (2006)
			Design for biological and technical cycles	Bocken et al. (2016), McDonough and Braungart (2002), Braungart et al. (2007)

B.2. Den Hollander's theory on the design for preserving product integrity

den Hollander (2018) states that a product's lifetime is often seen as the time during which a product is functional but functionality is an insufficient criterion because products are discarded while still in perfect working order and products can be temporarily out of order without the need to be discarded immediately. Only 22% of the products that are replaced is completely malfunctioning. Therefore he proposes to define a product's lifetime in terms of obsolescence. Where a product becomes obsolete if it is no longer considered to be useful or significant by its users (Burns, 2010). den Hollander (2018) claims that by following the Inertia Principle and the concept of product integrity, designers should initially aim to prevent a product from becoming obsolete and secondly, when the first goal cannot be fulfilled, make sure the resources can be recovered with the highest level of integrity. If this is done at the level of products and components, this is referred to as Design for Preserving Product Integrity. When this is done at the level of materials, it is referred to as design for recycling. This is shown in Figure B.1.

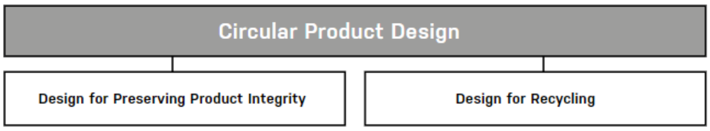

Figure B.1: "Circular product design includes both design for preserving product integrity and design for recycling" (den Hollander, 2018).

When looking at the design for preserving product integrity, three different ways are distinguished; Resisting Obsolescence, Postponing Obsolescence, and Reversing Obsolescence. The three different views are shown in Figure B.2. Each of the three design directions is supported by multiple design approaches which all aim to facilitate a specific intervention for preserving product integrity. These design approaches show overlapping pillars with the design approaches reviewed by Moreno et al. (2016) and will be included in the table. In subsection 4.4.2, essential design strategies related to the 10R framework will be elaborated upon.

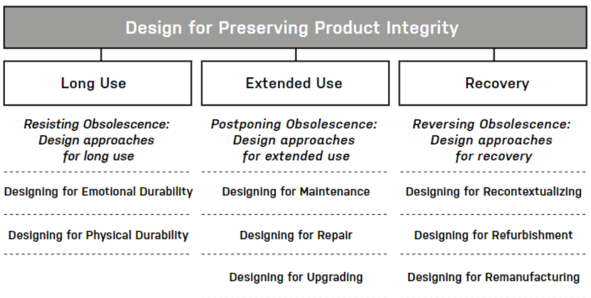

Figure B.2: "A typology for design approaches for preserving product integrity in a circular economy" (den Hollander, 2018).

To map and gain insight into these design directions, den Hollander (2018) proposes visually representing the overall design intention for preserving product integrity by plotting it in a three-dimensional design space. This is possible since all three design directions are in practice always intertwined. The 3D design space is shown in Figure B.3.

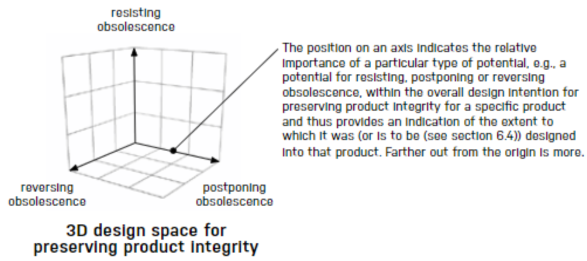

Figure B.3: 3D design space for preserving product integrity (den Hollander, 2018)

den Hollander (2018) has plotted a number of example products such as "throwaway" products, the Fairphone, the Eastpak backpack, and a Miele washing machine. Unfortunately, no clear method of mapping these products is available. This makes it hard to map maritime systems objectively and be able to compare them except for a rough estimate. Next to that, when mapping a product in one of the three directions, this is a combination of multiple design strategies, but in the mapping this distinction is gone, making it hard to see in which direction improvements should be made. Also the mapping does not include recycling/recovery and focuses only on the circularity during the lifetime. However, the terms den Hollander (2018) uses are quite similar to the 10R framework, but the 10R framework shows a clear distinction for prioritising design strategies and also includes the inflow of materials in the first three pillars of refuse, reduce, redesign, which den Hollander does not mention. Therefore in the next section, the design strategies as shown in the general overview and the design strategies of den Hollander (2018) will be combined and linked to the 10R framework.

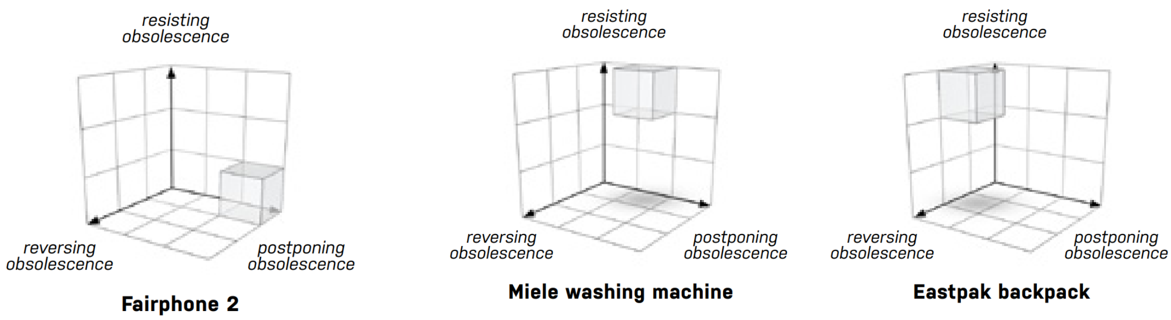

Figure B.4: Example products plotted by den Hollander (2018).

C

System life-cycles with associated stakeholders

It can be concluded that the chosen sub-systems can be divided into two categories; Unique products and Multiuser products. A Unique product is identified as a product that is designed specifically for this vessel type and which cannot be used on other vessels, an example being the windows and superstructure. A multi-user product is a product that is usable in multiple vessel types or maybe even other types of systems, an example being the captain's chair and the floor. These two products have different life cycle because the design and manufacturing process is not the same. Multi-user products can be built in stock whilst unique products are built once the product has been sold. In this attachment, four material flows are visualised for both unique and multiple-user products.

The material flow is visualised from a shipbuilder's perspective. The colours of the stakeholders show whether it is an internal or external stakeholder. The blue stakeholders are internal and the orange ones are external. These stakeholders are identified quite globally and don't show a great level of detail. The figures C.2 and C.1 show the current situation, but to shift to a circular approach, the flows will also have to shift from linear to circular loops. The circular loops are shown in Figure C.4 and Figure C.3. In this shift, the connection needs to be made between the end-of-life stage and the design stage. This connection is not necessarily a material flow connection but needs to be a knowledge connection.

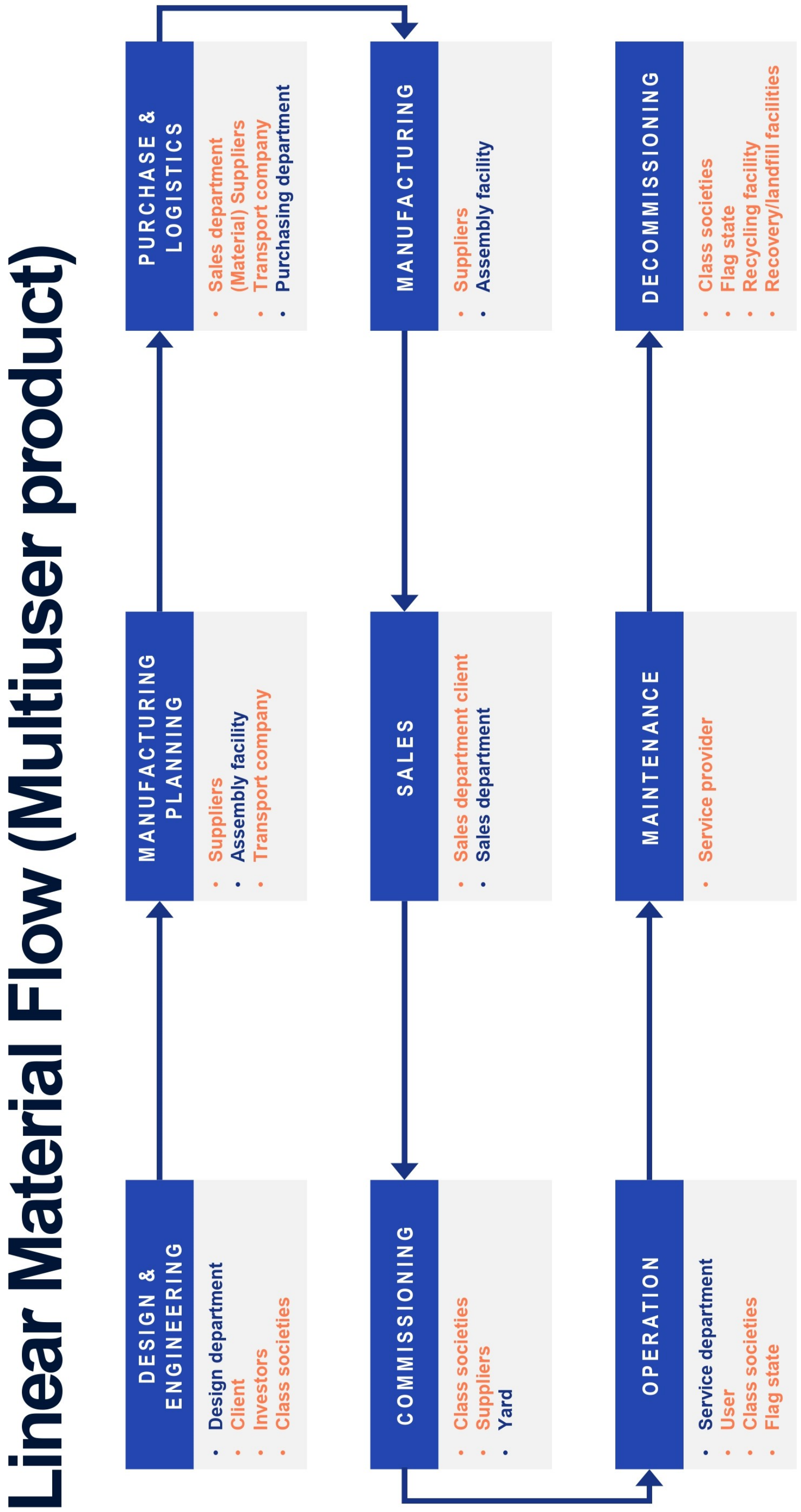

Figure C.1: Stakeholders in the linear lifetime of a multiuser product

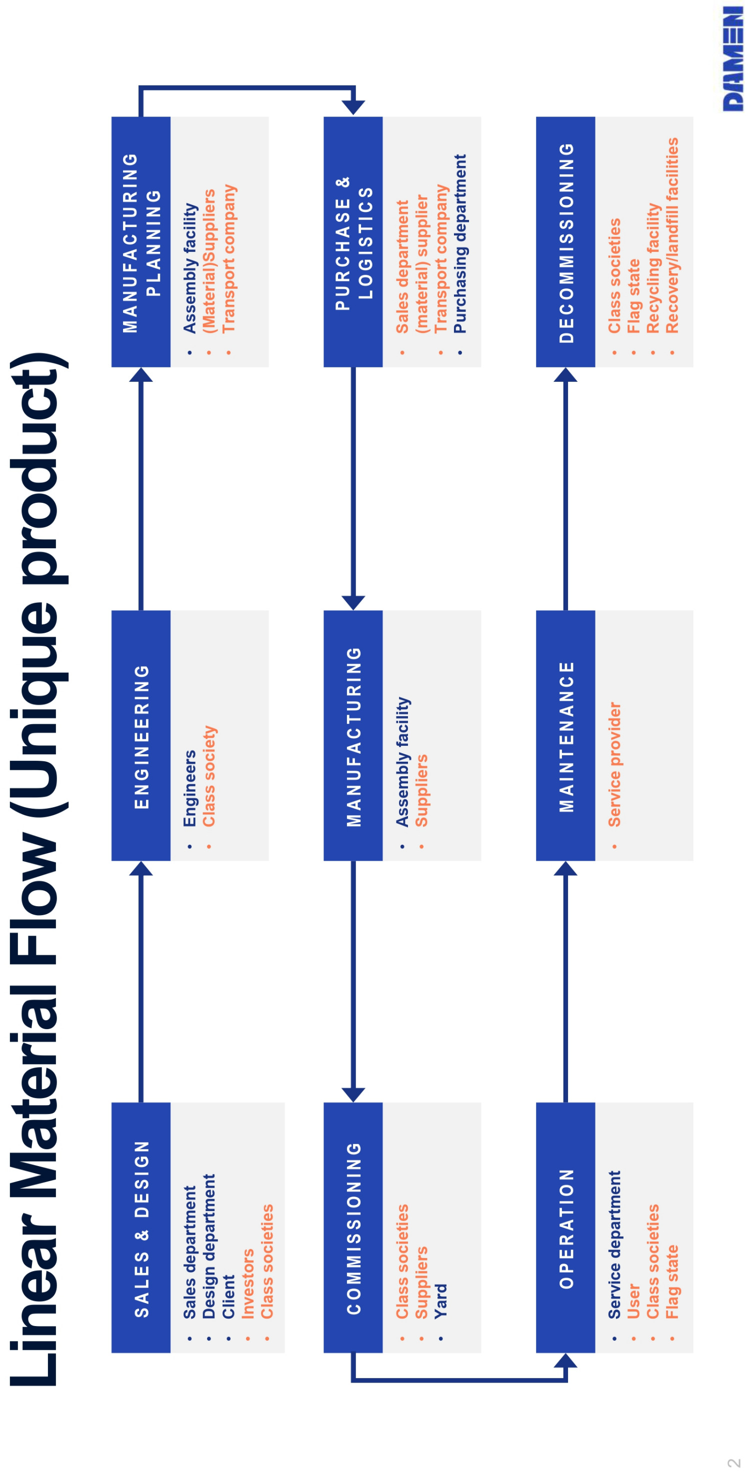

Figure C.2: Stakeholders in the linear lifetime of a unique product

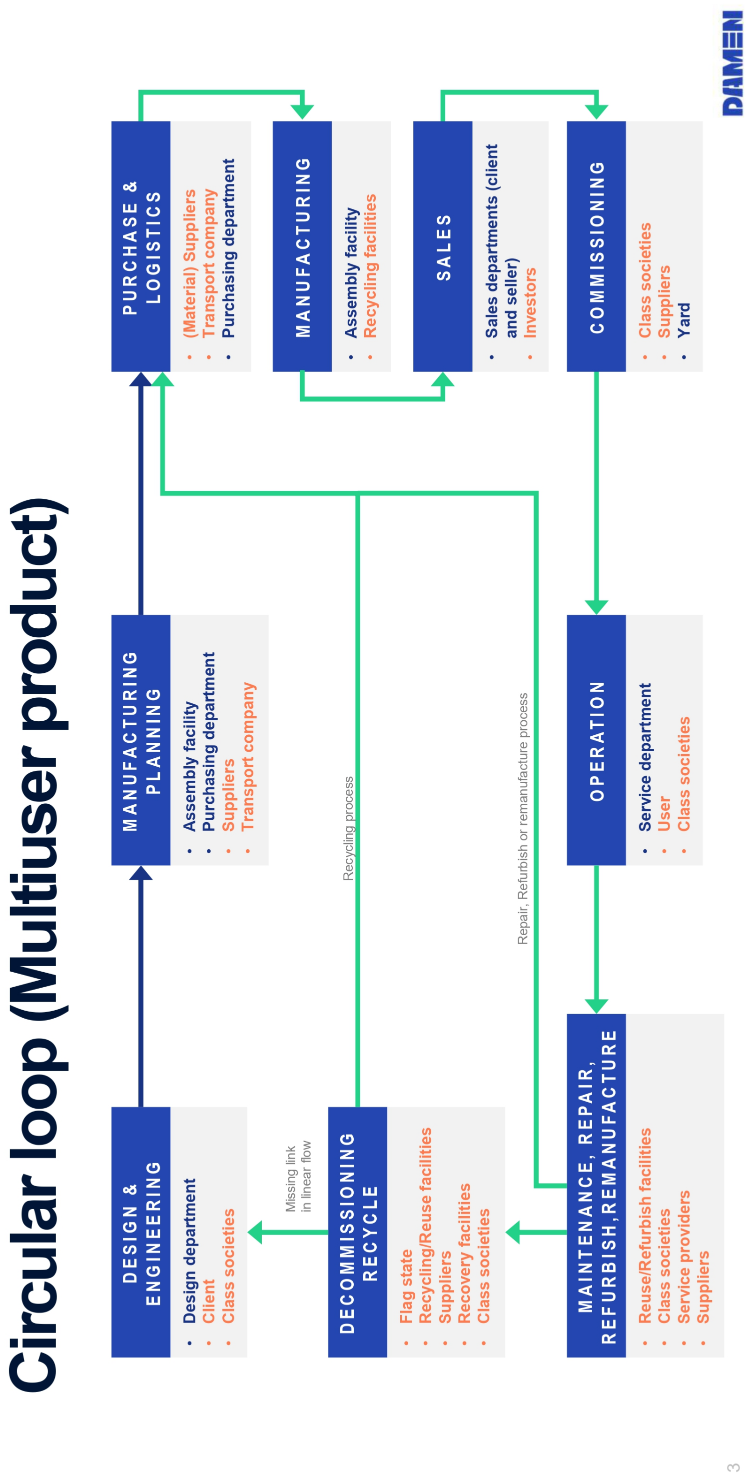

Figure C.3: Stakeholders in the circular lifecycle of a multiuser product

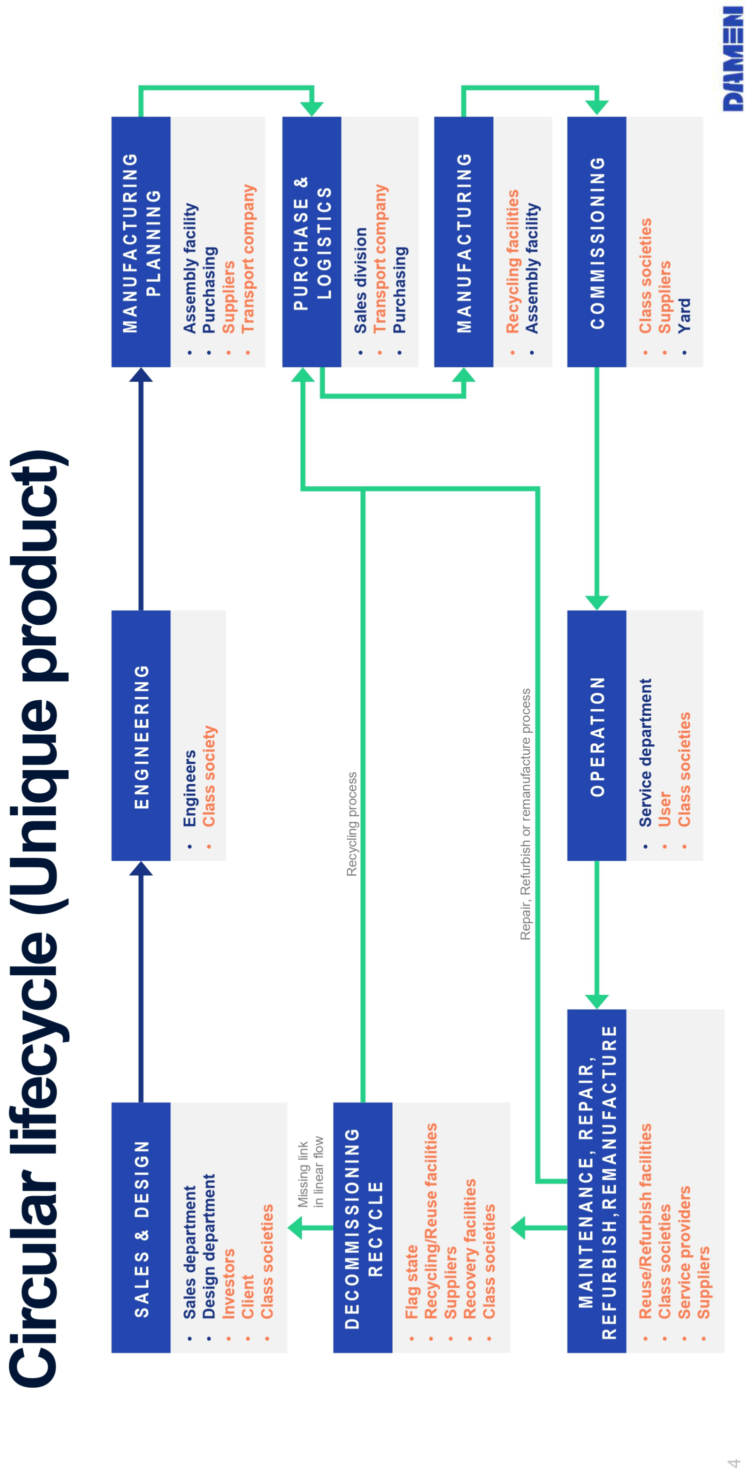

Figure C.4: Stakeholders in the circular lifecycle of a unique product

D Case study

This appendix includes the attachments for the calculations in the case study. The first section contains the detailed MCI calculation of the five sub-systems in the wheelhouse. The second section shows an effort summary regarding the complete case study.

D.1. MCI calculation for the wheelhouse

In this section, the complete MCI calculation for the 5 sub-systems in the wheelhouse is shown. The blue-filled cells include information provided by suppliers. The other percentages were estimated by use of industry averages aquired from the Ansys Granta Edupack database.

Table D.1: Detailed overview for the MCI calculation of the five sub-systems

				Inflow				Outflow					MCI
				Virgin	Recycled	Refurbished	Remanufactured	Refurbishment	Remanufacturing	Repurposing	Recycling	Recovery	
System	**Sub-system**	**Components**	**Parts**										
Wheelhouse	Chair captain	Seating chair	Seat cushion	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	50,00%	50,00%	0,25
			Backrest	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	50,00%	50,00%	0,25
			Armrest top	25,00%	75,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,875
			Extruded frame										
			Cast frame										
			Connecting bolts										
		Deck rail	Rail	30,00%	70,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,85
			Sliding parts										
			Wagon										
			Connecting bolts										
			Snap in covers										
			Brake cable										
	ASSY Console	Hatches	Rubber profile hatch	81,50%	18,50%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,5925
			Rubber profile ventilation hatch										
			Hatch with ventilation										
			Hatch										
			Compression latch										
			Cam, without catch, without recess										
		Console Enclosure	Handrail										
			Lower console part										
			Upper console part										
			T-bar lower console part										
			T-bar upper console part										
			Metal mounting plate: divider										
			Metal mounting plate: Long side										
			Metal mounting plate: Front										
			Metal mounting plate: short side										
			Stud bolts										
		Fan	Fan DC										
			Fan cover										
		Top plate	Gas spring										
			Rubber profile										
			Top plate										
			Hinge										
	Windows	Glass windows	Glass panes	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,5
			Cover lists	63,00%	37,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,685
			Retaining list	63,00%	37,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,685
			Frames	63,00%	37,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,685
		Window wipers	Window wiper motor	80,00%	20,00%	0,00%	0,00%	0,00%	0,00%	80,00%	20,00%	0,00%	0,6
			Window wiper blade										
			Window wiper arm										
		Sunscreens	Bracket for solar curtain	80,00%	20,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,6
			Solar screen										
			Cheese head screw										
			Self adhesive film										
	Superstructure	Superstructure	Plates	63,00%	37,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,685
			Stiffeners										
		Isolation	Isolation material	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	80,00%	20,00%	0,4
			Insulation fastener										
			Adhesive tape										
			Coating										
	Floors	Floating floor Sika	Sikafloor marine 570 (A and B compnents)	80,00%	20,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,1
			Intergard 269										
			Electro galvanized steel plate 2mm										
			Bonding adhesive (Sikaforce-472 FR L60)										
			Electro galvanized steel plate 3mm										
			Steel strip										
			Insulation (Isover USP96)										
			Self leveling mortar 190										
			Marine primer C										
			2cm VEM										
			Glue (Sikaforce 472)										
			Glue (Sikaforce)										
		Floor covering	Sikafloor marine 540	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0
			Coating, Coloured chips										
			Sikafloor marine-505										
			Sikafloor marine-590										
			Sikafloor marine-002 booster										

D.2. Effort summary

In this section, an effort summary is given for the case study. Two figures are shown; Figure D.1 shows a chart with time divided over the different steps visualised as percentages. It stands out that especially step 3 took a long time. This is the step where the system is broken down into subsystems, components, parts, etc. To see what it is specifically that takes a lot of time, Figure D.2 has been added where steps 1 to 6 are split out in more specific actions. Looking at this figure, it becomes clear that especially gathering information is a very time-consuming activity. Also because this information has to come from many different sources and is not organised in a way that it can directly be used for the framework. Next to that, even when information is gathered, it might not be complete and more time needs to be spent on finding the rest of the information. This is also seen in the light green pizza point where, next to translating all the information into a physical redesign, the most time was spent on. Translating the information into a physical redesign was a time-consuming process because of the lack of knowledge of the technical possibilities that are available to create a more circular design of a floor. All in all, it is estimated that a total time of 350 hours was spent on the case study.

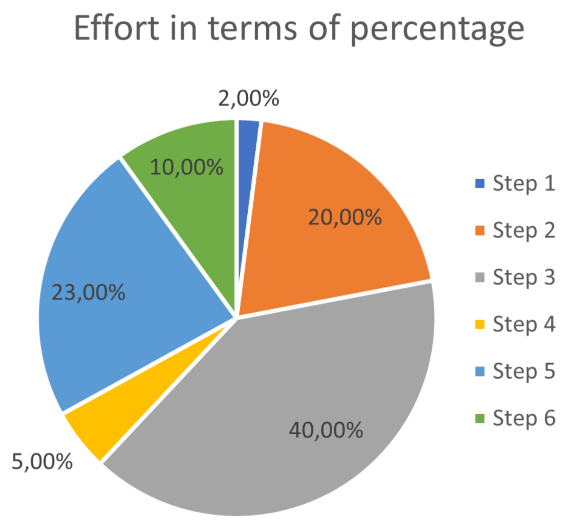

Figure D.1: Effort of conducting the case study expressed in percentages of time spent on each step.

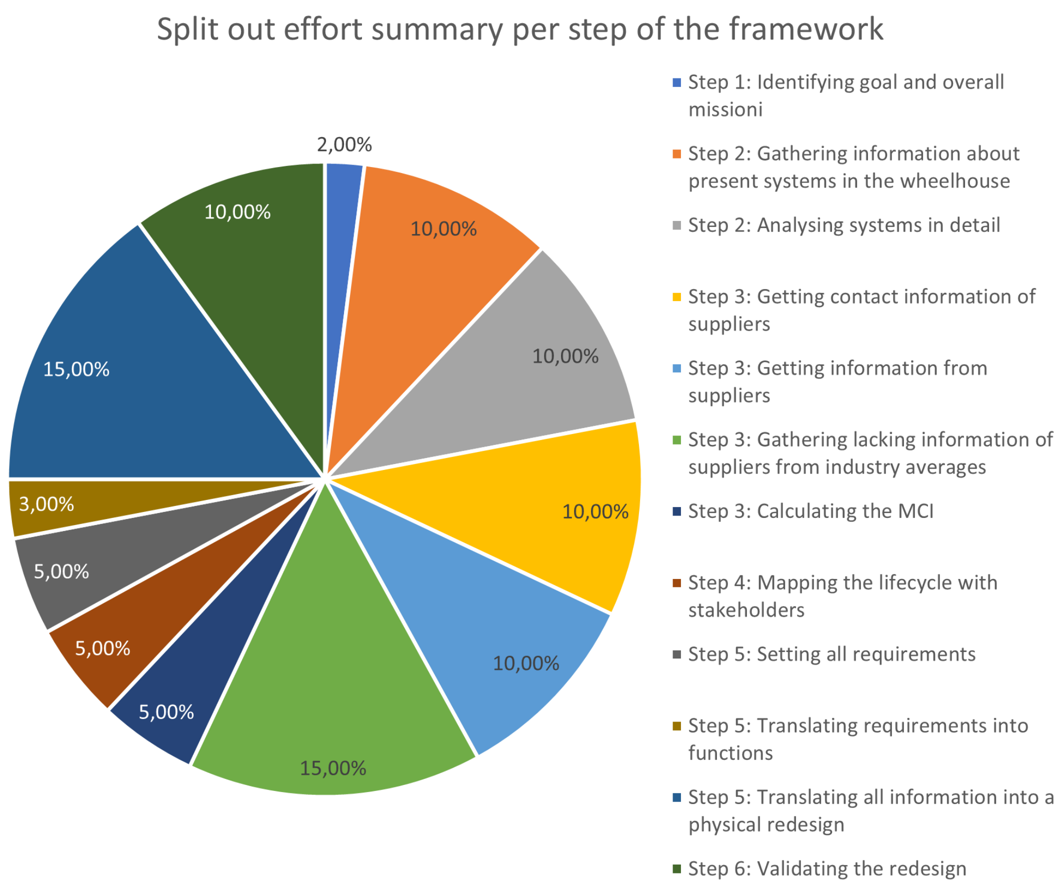

Figure D.2: Effort of conducting the case study expressed in percentages of time spent on each step split out in activities per step.