Technische Universiteit Delft

The footprint of yacht production

Defining a framework for the Yacht Environmental Transparency Index

E.J. Cozijnsen

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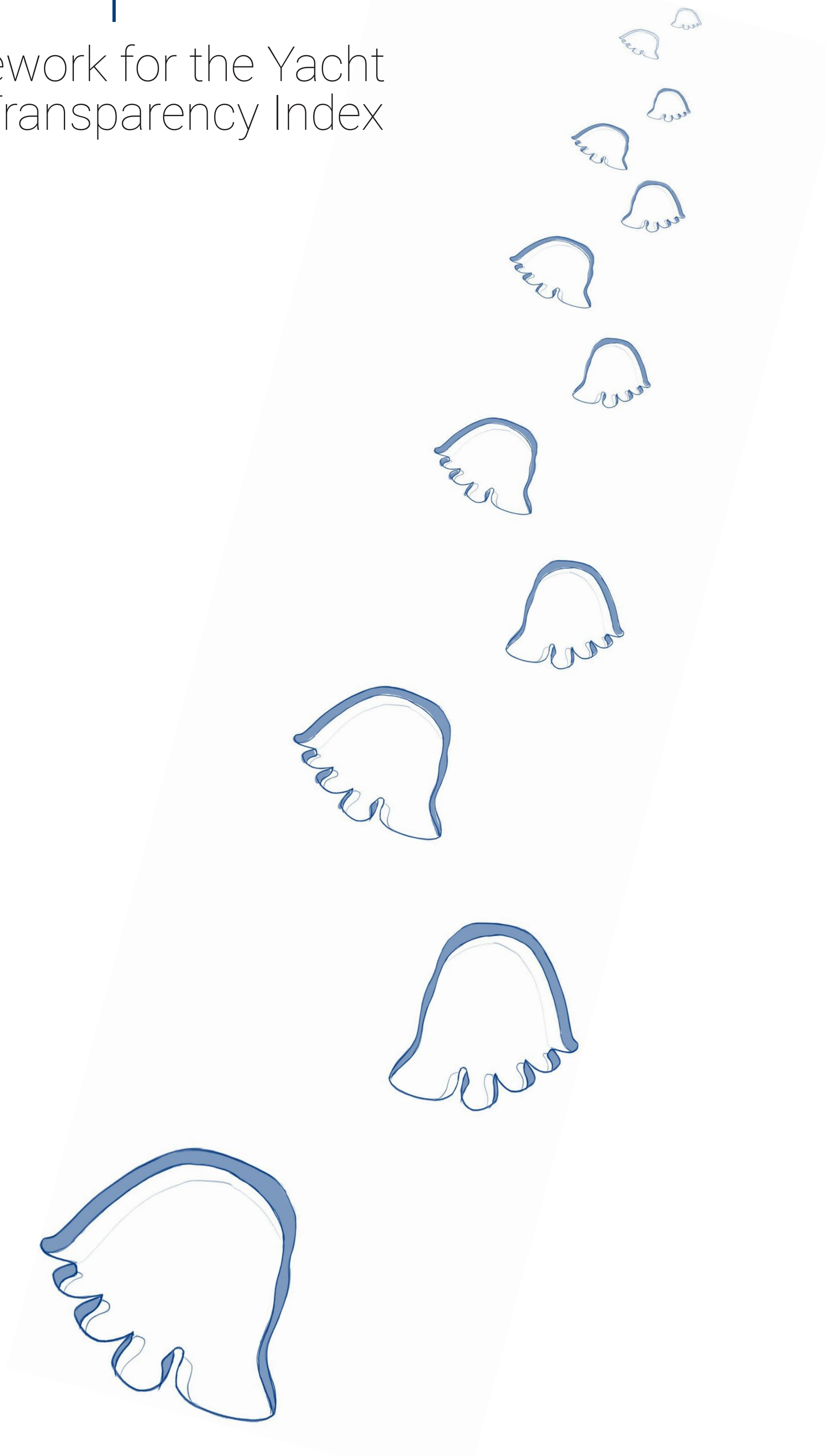

Thesis for the degree of Msc in Marine Technology in the specialization of Production.

The footprint of yacht production

Defining a framework for the Yacht Environmental Transparency Index

by

E.J. Cozijnsen

Performed at

De Voogt Naval Architects

This thesis SDPO.19.036 is classified as confidential in accordance with the general conditions for projects performed by the TUDelft.

Delft, December 17, 2019

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Preface

This report is part of the MSc thesis project to obtain the MSc degree Marine Technology at Delft University of Technology. This thesis project is performed at De Voogt Naval Architects in collaboration with the Ship Design, Production and Operations section of the Delft University of Technology. The subject of this thesis is of my own personal interest: The footprint of yacht production.

This research is aimed to contribute to the creation of the an environmental index for yachts, referred to as the YETI: Yacht Environmental Transparency Index. The entire initiative of the YETI aims to assess the total life cycle of a yacht, while this thesis only focuses on the environmental impact from yacht production. This report is intended for readers with an interest in assessing the environmental impact from yachts. The model for the assessment of yacht production is described in chapter 4. The sensitivity of this model to design choices and the influence of the chosen system boundaries is investigated in chapter 5. Finally, chapter 6 gives the conclusions and recommendations on the model designed for the YETI. Some of the information used for this thesis is confidential and the appendices including this information are therefor not provided.

I would like to express my gratitude to both Jeroen Pruyn and Bram Jongepier. First, for being open to the subject and helping to make it possible to research the footprint of yacht production. Second, for the supervision, guidance and interesting discussions throughout this research. I'm also grateful to Feadship and De Voogt Naval Architects for providing me with a work environment that was inspiring and very open to share knowledge. Furthermore I would like to thank Gijsbert Korevaar and George Tsalidis for helping me get more familiar with the environmental assessment methodologies.

Finally, there are a few individuals deserving of a word of gratitude. Starting with Guus, for all the "intern coffee moments" which helped to keep us motivated. Danique and Linda for the support and for reading my report. Pieternel deserves a word of grace for checking my English. And last but not least Martijn for being there for me throughout this whole process and always giving me new motivation when I got stuck.

Elizabeth Johanna Cozijnsen
Delft, December 17, 2019

Summary

This research has been performed with the goal to set up a model for the comparison of the environmental impact caused by the production of yachts. This model is created in such a way that it can be implemented in the YETI, Yacht Environmental Transparency Index, which is currently under development. The model that is created is based on a life cycle assessment methodology named Fast Track LCA. This methodology is an adapted version of the classical full and rigorous assessment as defined by the ISO and focuses on making comparison of the results possible.

The aim of the YETI is to assess a yacht's environmental impact over its life span. The life span includes activities that can be related to the production and operational use of a yacht. The impact from operational use is outside the scope of this thesis. The life cycle of a yacht with only activities that can be related to the production is standardized as follows: After the building, maintenance takes place every 2.5 years and 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. Meaning that the life of the yacht ends and that refit activities create a new yacht.

System boundaries about this life cycle exclude all yard processes from the assessment, excluding energy required, yard processes, transport and material efficiency. Excluding these yard processes ensures that the YETI will underestimate the impact caused by yacht production. Results show that the effect of including the energy used for hull construction and assembly of the yacht would increase the environmental impact by 40%.

Part of the Fast Track LCA methodology is the quantification of materials and this research presents a standardized framework for this inventory. The Framework is used to ensure that the same input is used for every YETI assessment. The input required is based on the type and amount of materials used in the building phases. Because of the standardized life cycle the rest of information on maintenance and the end of life scenario is calculated automatically. For more complex items such as ship systems the material choices are predefined in the framework for the LCI. The definition of a standardized framework with predefined material choices makes the model more transparent, understandable, usable with minimal effort and ideal for comparison. However it does not fulfil the requirement of having no room for manipulation. The model is highly sensitive to the input data, meaning that if the input data is not correct, the outcome of the model is not either. No solution is found to eliminate this form of manipulation.

The model created for the YETI to calculate the environment impact is applied on the case study of yacht A, a yacht build in recent years by Feadship. The results were validated by comparison with a previous study. As the YETI should show different scores for different designs, a sensitivity check was performed. The study showed that the model is sensitive enough to design choices. Furthermore, it is likely that the impact from production will grow due to measures to lower the operational impact from yachts. The outcome of the model is suitable for comparison. However, the outcome itself is an underestimation of the real environmental impact from yacht production. This is due to missing environmental data of used materials and the exclusion energy for both the production and the recycling.

Concluding, the model created in this research makes it possible to compare yachts based on their environmental impact from production. However shortcomings in the model are found due to the limited availability of information of materials used in yachts. This can be solved by doing more intensive environmental studies into the materials and products used for the construction of yachts. Additionally the assumptions on the predefined materials for ship systems have to be validated by checking the distribution of materials for other yachts. For further use of the YETI it is recommended that yards and designers change the way they keep track of used materials. This will make future use of the YETI more easy and accurate.

Abbreviations

EEDI	Energy Efficiency Design Index
EPD	Environmental Product Declaration
GHG	Green House Gas
IHM	Inventory of Harzardous Materials
IMO	International Maritime Organization
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
PCR	Product Category Rules
YETI	Yacht Environmental Transparency Index

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1
Introduction

The maritime industry as a whole is known to be a big contributor to the total amount of Green House Gases(GHGs) emitted. The International Maritime Organization(IMO) has estimated that over the year 2012 the total amount of CO_2 emitted by shipping is 938 million tons which equals 2.6% of the global total amount of CO_2 emitted [37]. The shipping industry has so far not been included in the major environmental agreement of the united Nations: The Paris Agreement [66]. In order to express the importance of carbon emissions reduction of the shipping industry in another way the IMO has taken the lead by setting up a strategy on the reduction of Green House Gases (GHGs) [38]. In this strategy three goals are highlighted: First the IMO wants to further implement the Energy Efficiency Design Index(EEDI), second the IMO has the ambition to lower the CO_2 emissions of the shipping industry by 40% in 2030 and 70% in 2050. The third, and final, goal is to reduce emissions of all greenhouse gases by 50% in 2050. Though being a big contributor to the GHG emissions shipping is also a big contributor to other environmental impacts. For this reason the international convention for the prevention of pollution from ships (MARPOL annex VI) regulates the pollution by air of SO_x, NO_x and particulate matter [36].

However, all these measures are taken in order to reduce the environmental impact of shipping and do not take the emissions of the shipbuilding process into account. Shipbuilding is not part of the shipping industry because it is land based, and thus falls under the Paris agreement and should therefore reduce its environmental impact. But, as will be discussed in paragraph 1.2.1, there is a limited amount of information available on the emissions from ship production. As a result there are uncertainties on the proportion of the environmental impact of the ship production in comparison with the operational impact.

Although yachts are vessels, they are not really part of the shipping industry for the basic reason that their purpose is not to ship anything. Yachts are designed for pleasure unlike other non shipping vessels like tugs. The goal of a yacht is to provide an amount of luxury space on water at reachable places in the world. This difference with regular vessels translates in a completely different operational profile in which energy is used more for the comfort of guest on board than the propulsion.

In order to lower the carbon intensity of the maritime industry the IMO has made the calculation of the Energy Efficiency Design Index mandatory in 2018 for the applicable vessels [38]. This index aims to promote energy efficient, or in other words less polluting, solutions on board ships. The expression of the EEDI is in CO_2 emissions per ton shipped over a nautical mile. Due to the difference in operational profile the expression of emissions from yachts in shipped tons over nautical miles becomes complicated and inaccurate. From this gap between existing indices and the willingness to make yachts more sustainable the idea to make an index for the yachting industry was born. In order to push the industry to create more sustainable designs, to set a standard and to make different yacht designs comparable Feadship has initiated the search for the YETI, the Yacht Environmental Transparency Index.

This chapter will give more information about the YETI, its goal and requirements. As the YETI will focus on the assessment of the environmental impact this chapter will discuss different initiatives that have already tried to create a framework. There is regulation that will require yachts to document some materials that are used. It is important to take note of how this regulation get implemented. Also, there are different in-house investigations done by De Voogt that give insight on important considerations for the assessment of yacht specifically which will be discussed in this chapter.

1.1. The YETI

The YETI is an industry initiative with the goal to push the yachting industry to become more sustainable. To reach that goal, one of the first steps is to chart the balance between a yacht and its environmental footprint. The general idea is that the YETI provides an easy-to-use index that shows the environmental impact of a yacht. At the same time it allows for comparison between yachts with the expectation that it can help the industry towards designs with a smaller environmental footprint.

The idea of the YETI was developed in November 2018. In the past couple of months agreement was reached about a very basic frame work for the YETI. In a joint industry project it was agreed that the YETI should comply with the following points as listed below. The next paragraphs explain the YETI abbreviation in more detail.

- Easy to use method
- Method needs to allow for comparison between yachts
- Able to account for different yachts, in size and propulsion method
- Transparent
- Environmental impact from a life cycle perspective
- Indifferent about comfort, luxury, safety, size, top speed, number of passengers and fun

The Y

A yacht can be defined as an amount of luxury space for the pleasure of the owner, which can be relocated under its own power. It has a certain area and volume, is cooled or heated as required, contains accommodation, leisure areas and equipment. As at this level of yacht design and building every yacht is (almost) fully custom. Because yachts are custom designed and built, the YETI should be applicable to a wide range of size, speed character, propulsion layouts and exotic designs.
For the YETI a ship is considered a yacht when it is designed for the pleasure of both paying and non paying passengers, is crewed all year round and needs to have the ability to cross the Atlantic Ocean independently.

The E

The YETI says something about the influence of the yacht on the environment, this is called the environmental impact of a yacht. Emissions commonly linked to the shipping industry are green house gases, SO_x, NO_x and particulate matter. These emissions are part of the regulations enforced by the IMO. However, not only emissions are environmental impacts but the depletion of resources or the radiation of underwater noise from vessels are considered impacts as well [28, 47]. For the YETI, a list of relevant environmental impacts for ship production and operation will have to be determined.

The T

When designing the YETI one of the challenges is how it can be designed for future use without enabling future engineers to manipulate the index. The YETI will be designed to use for all future yachts and will thus have to be made in such a way that it will still be considered a valid index in a few years. If in a few years a lot of loopholes are discovered the YETI will lose its credibility.
Transparency is one of the main requirements of the YETI and concerns many of its aspects. From every life stage the information and data used, but also the method itself will have to be transparent. As an example the speed power curve of a yacht is checked during the sea trial and thus says what the actual required power is. But how can the same check be done to know if 430 or 450 ton steel is used? During the design process of the YETI a balance has to be found between accessibility of data and sensitivity of the index. Higher sensitivity would allow incorporation of all the small initiatives for more sustainable yachts and yacht production, but would also require so much more documentation of data. This balance can also be influenced by a third party, such as a classification society or an foundation like the Water Revolution Foundation.
For this research it is important that for all information and data the following three questions are answered:

- How can the information or data be obtained?
- What is done with the information or data?
- Is the information or data verifiable?

The I

In this stage of designing the YETI it is assumed that the YETI will be one index, either a score or a label based on the calculations of environmental impacts. The YETI should be applicable to all kinds of yachts because there are significant differences between designers, yards and even yachts. The focus on customization in the yachting industry makes it hard to compare yachts both in size and operational use. Still, comparison can only be done if the outcome of the YETI is expressed in the same unit for all yachts. Taking this general description of how the YETI should look gives the expression as given in equation 1.1.

$$\text{YETI} = \frac{\text{Impact}}{\text{Use}} \tag{1.1}$$

1.1.1. Requirements

The YETI will be further designed with a groups of super yacht builders, designer and knowledge institutes through a Joint Industry Project. During meetings of these participants requirements for the YETI are discussed. These wishes from the industry and the requirements from literature are analyzed by Letschert [44] and listed below.

1. The calculation method should be transparent
2. The YETI should remain as simple as possible for both understandability and minimizing the effort for calculation
3. Design of the YETI should be in such a way that manipulation is not possible.
4. Results should be obtained through standardized processes and data has to be verified through standardized methods.
5. The YETI should be designed for comparison

These requirements have to be used for the design of the YETI framework.

1.2. Environmental impact of ships and yachts

The YETI initiative is not the first that takes a look at the impact that is caused by shipbuilding and shipping. The emissions caused by the operational use of ships is commonly known, but the impact caused by ship building is relatively unknown. In research, discussed in more detail in this paragraph, frameworks for the determination of the impact from ship building are defined. However, most literature highlights that the information about ship building is lacking and that research has not resulted in a standard for the assessment of ship building. For the YETI the previous research can be used as input, but a new framework will have to be defined based on the requirements of the YETI. Previous research also shows the need for an analysis of the results gained with the framework in order to enlarge the knowledge about the impact from yacht production and ship production in general.

1.2.1. General research

Research on the environmental impact from ship building is often found in combination with the impact from the operational use of a vessel. This is commonly done in a Life Cycle Assessment (LCA), a method that has been standardized by the ISO in the 14040 [39] and 14044 series [48]. Already in 2002 Fet [24] concluded that LCA can be applied on a ship and between then and 2010 others have researched maritime applications of LCA. In 2005 the importance and opportunities of LCA for the shipbuilding were determined by Shama [60] and LCAs have been made for the shipbuilding and shipping industry by Gauss [26], Ellingsen [22], Michihiro [42] and Tincelin [64]. Later Chatzinikolaou and Ventikos [18] have researched the application of LCA for a panamax oil tanker. One of the conclusions of those studies is that the environmental impact of the shipbuilding process is only a few percent of the total environmental impact of a vessel over its lifetime. An estimation can be made that this percentage is somewhere between two and eight percent. However, there are a lot of different ways used to express the environmental impact. For example, Ellingsen researched the total environmental impact expressed in terms of Eco indicator 95, which gives a method to add up different environmental impacts. On the other hand, Chatzinikolaou and Ventikos give the emissions per specific substance, such as CO_2, CO, VOC, CH_4 and six others. With CO_2, CO, NO_x and SO_2 having the largest contributions to the total emissions measured in ton [18]. This is not the only difference between these studies, the level of detail differs per research as well. For these reasons it is hard to make a better estimation than the expected range of two to eight percent of the environmental impact coming from ship production.

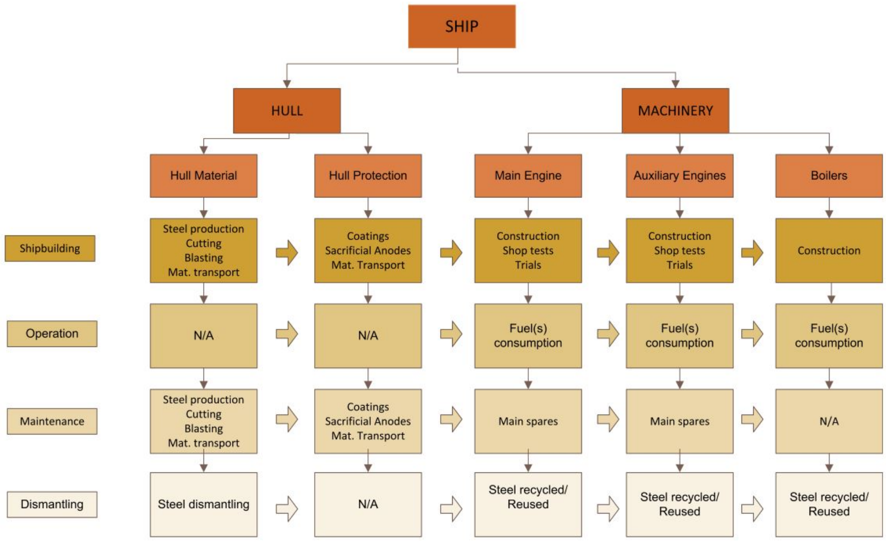


Figure 1.1: Structure of the ship system by Chatzinikolaou and Ventikos [18]

In 2013 another article of Fet [25] was published in which a number of initiatives to create a framework for the calculation of the impact of ships, some including production, are discussed. Included in these initiatives are Sustainable Ship Design(SSD) and LCA Ship, which respectively have three [22, 64, 65] and one [40] related documents showing in an internet search. Only the document on LCA ship fully explains the method that is developed. This shows that although these methods are developed they are not adopted into the maritime industry. For this reason Fet concluded the paper highlighting that while there were initiatives, a holistic approach for more sustainable ship design is still lacking. Subsequently, Chatzinikolaou and Ventikos [18] published a holistic framework in 2015 that uses LCA to calculate the air emissions of a ship. The framework is shown in figure 1.1 and is based on the ISO standards and Systems Theory. Their results for ship production are split in material use for the hull material and hull protection and the hull material is split in steel production and the basic production activity's (welding, cutting, blasting and transport). The results are dominated by the production of steel for all the emissions that were considered. However, it was highlighted that data availability for production was a problem and should thus be the focus of further research. The framework looks promising but for the YETI it should be investigated whether it is sufficient to only consider steel production, the production processes and hull protection or that there will be other factors, such as materials for interior and exterior, that are expected to have a large contribution as well.

Though there have been multiple attempts to create a framework for the assessment of the impact on the environment from ship production, non have become common practice. On the other, hand all studies emphasize that using LCA in the shipping industry can be useful as it can locate where in the vessels life time improvement is possible in terms of the environmental impact. Another interesting conclusion drawn in these studies is that there is a lack of information on the production process, which is crucial for a good LCA. The final conclusion that can be drawn is that despite previous research it is still not clear what the real impact is from ship production.

1.2.2. Environmental product declaration

Indirect, there has been another attempt to create a framework for the assessment of yachts specific. This was done in order to make it possible for yachts to obtain an Environmental Product Declaration (EPD). Three different types of EPDs have been defined by the ISO. Interesting are the type III environmental declarations which present quantified environmental information on the life cycle of a product on a voluntary base to enable comparisons between products fulfilling the same function [32]. The basis of these comparison is a LCA done according to the ISO14040 standards. A product that has an EPD has been assessed according to the standards, this does not mean that the product is sustainable. The objective of these EPDs are:

- To provide LCA-based information and additional information on the environmental aspects of products.
- To assist purchasers and users to make informed comparisons between products; these declarations are not comparative assertions.
- To encourage improvement of environmental performance.
- To provide information for assessing the environmental impacts of products over their life cycle.

In order to obtain an EPD the product has to be assessed according to a set of rules, requirements and guidelines which are specific for one or more product categories, these are called Product Category Rules (PCR). The PCR gives more information on what should be included and excluded for the assessment of a product group. According to the ISO standard the PCR gives the specific rules for the use of a functional unit, system boundaries and all the other items listed in the scope definition of the ISO14040.

The PCR for yachts takes both operation and production into account and provides interesting insights in system boundaries and a product break down structure. Both will be used later in this research. The LCA based on the PCR is a very detailed assessment. The framework from Chatzinikolaou and Ventikos in figure 1.1 gives a simplified number of systems to consider which makes the assessment easier and quicker. The use of such a framework complies with the requirements for the YETI listed in paragraph 1.1.1. Such a more detailed framework that has predefined which systems are in- or excluded standardizes the YETI methodology and keeps calculations more simple. The full LCA required for the EPD will require much more time and effort.

1.2.3. Inventory of Hazardous Materials

One of the conventions of the IMO currently waiting for acceptance is the Hong Kong Convention [35]. Part of this convention is the requirement of an Inventory of Hazardous Materials (IHM) on board. Although this convention has not entered into force, the European Union have made their own regulation on ship recycling in which every ship entering an European harbor has to have an IHM. This EU Ship Recycling Regulation [11, 12] states that from 2013 onward every ship under an European flag should have an IHM on board. Starting from December 31st 2020 this will be the case for all ships under all flag states that want to enter an European harbor.
There are two parts of the IHM, part I and II, of which part 1 refers to the design and construction phase of yacht [33]. The substances for which it should be assessed whether they are embedded in the yacht are listed in table A and B of the IHM. Currently the Feadship yards are working on gathering information from all suppliers and investigate in which items and systems the substances from table A and B are enclosed.

The reason this regulation is interesting for the YETI is that it also requires detailed information on the materials that are used on ships. However, the best way for the yards to gather the information is asking their suppliers about the materials that are used in their products. This process is currently starting and thus provides opportunities to gather more information that could help for the development of the YETI with respect to information on materials.

1.2.4. In-house research

When looking at the research done at De Voogt, LCA is also the preferred method for the investigations into emissions from production, operation and dismantling. Two investigations took place in 2009, one on a concept yacht and the other for a yacht that has actually been built. Both are in the same range with lengths of 75.25 meter and 77.70 meter and have comparable breadth and draught (GT and displacement were not available for both yachts). The results are expressed in the same unit, called eco points. Eco points will first be explained in this paragraph after which both assessments will be analysed and compared.

Eco points

The term eco points comes from the assessment method called Eco-indicator 99 and is short for Eco Indicator points. In the Eco Indicator 99 method the impact is calculated to different aspects of the environment, called impact categories. More discussion on impact categories linked to the yachting sector is discussed in paragraph 4.4.2. These impact categories all have their own unit in which the impact is expressed. As a result it is not possible to add the impact of different categories to get one value for the overall impact. However, the Eco Indicator 99 method is created to weigh the impact of different categories to each other. The method developed is a weighting method which makes it possible to express all impact categories in eco points. Adding up the eco points gives the overall impact of all impact categories.

There are multiple ways for the weighting of the impact categories which translates in a difference in the amount of eco points that are linked to a kilogram of a resource. The weighting is based on social science and is therefore influenced by different cultural perspectives [27]. To keep the calculations transparent more detailed choices within the assessment method have to be defined as well.

Eco points and the Eco Indicator method were the standard for environmental impact assessments during the early 2000s and for this reason it is used in the assessments of the actual and concept yachts discussed in the following paragraphs. However, since then other methods have been developed and have taken the place of Eco Indicator 99 as common practice. More about the current methods can be found in paragraph 4.4.2.

Explanation of the assessment of the conceptual yacht

During the assessment of the conceptual yacht [31], hereafter referred to as yacht X, both the building and operational phase were included. This was because the goal was to see what the impact is of different propulsive methods. For both phases a base situation was defined which is taken the same as for all the different propulsion concepts and is analysed in this paragraph. The data about the eco points per kilogram of material come from the eco invent database, a database dedicated to Life Cycle Assessments.

The assessment of yacht X is limited to the original materials used in the yacht, including production of the materials, transport to the shipyard, construction and the transport of furnishings. This results in an impact from production that is approximately 1% from the total impact of the yacht over its lifetime including operational use. The recycling of materials reduced this percentage by 0.53% to 0.47%. During the research a maintenance and refit scheme was defined with the following intervals:

- Every year: Dry docking, cleaning the hull and replacing the anodes.
- Ever 4 years: Dry docking and repainting the whole yacht
- Every 10 years replacing the propellers
- An assumed life time of 50 years with two major refits during which the interior is replaced.

This maintenance scheme is responsible for 0.45% of the total impact of the yacht. Adding this to the 1% for construction and to the minus 0.53% percent due to the recycling of materials the total impact for production is 0.91% of of the impact of both production and operational use. This shows how little of the environmental impact of the yacht is defined by its production process. However, the assessment showed that the use of other propulsion systems (such as hybrid or diesel electric) increases the impact caused by the production of the yacht while decreasing the total impact over both the production and operational life cycle. It indicates that the share of the total impact caused by production will increase when choosing more sustainable propulsion systems.

To analyse the materials used in the production of the yacht, an overview of the materials with the largest impact was made. The overview is shown in figure 1.2. Striking is the influence of recycling, showing that proper recycling will make it possible to re-use a material and thus lower the environmental impact. Though not mentioned in the figure, the energy used for the production is actually the fourth biggest contributor to the environmental impact.

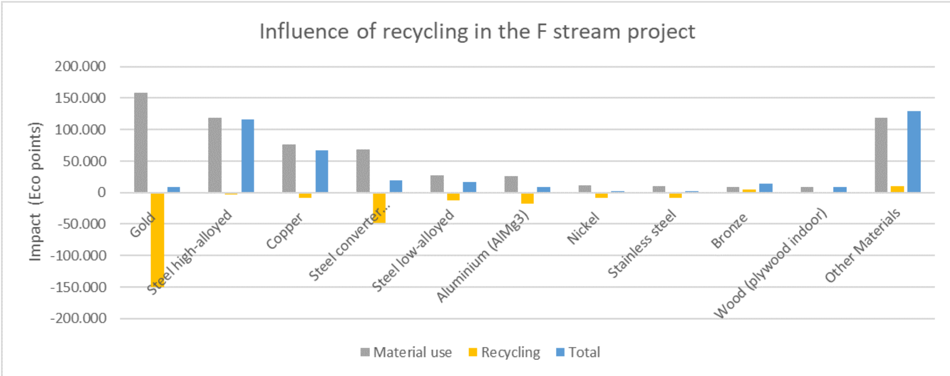


Figure 1.2: Results of material use on the yacht X

The assessment of yacht X was carried out in 2009 with the Eco Indicator 99 methodology. This method has stayed the same over the years but information on the materials used in the assessment has been improved. In order to check the influence over time, a new the assessment is done per kilogram of material. This is done to see the difference between the results of 2009 and when the same materials are assessed in 2019. The Eco Indicator 99 method has also evolved over the past years and Recipe is its successor. The results of the assessment of 2009, the results for the assessment with Eco Indicator 99 performed in 2019 and results obtained with Recipe are shown in figure 1.3. Significant changes can be seen in the impact per kilogram of material. This is important when comparing the results from assessments done over the years. For the YETI this would mean that the impact of a yacht assessed in 2009 and 2019 will differ even if the same materials and methodology is used.

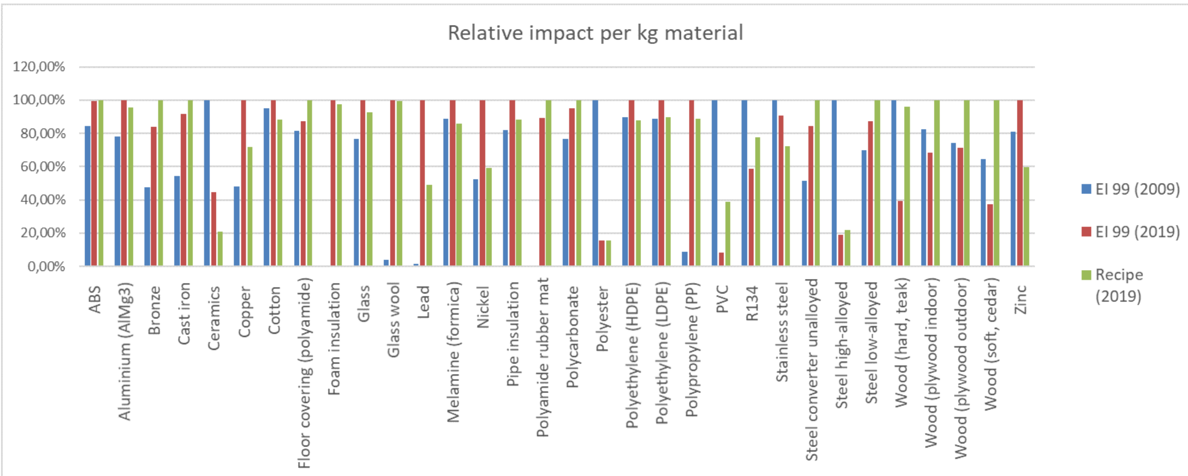


Figure 1.3: Influence of time and different assessment method on the results of the impact of materials per kilogram.

Explanation of the assessment of the actual yacht

The other investigation done in 2009 on the environmental impact from a yacht is done on a yacht actually build by Feadship [30]. This yacht will be referred to as yacht Y. The production process is researched separately from the impact of the operational phase of the yacht. For the building phase the materials are considered and the processing is taken into account by adding an extra percentage. The welding of steel plates, for example, the impact from welding is taken as 10% extra on the impact of the steel as an material. This method is not validated during the research and no sources are given to indicate on which other research these assumptions are based. If the processing would be included in the YETI procedure more information on these assumptions about processes is necessary.

In the life cycle there are significant differences compared to the assessment of the yacht X. The life time of the yacht Y is taken at 30 years and no maintenance activities are included in the life cycle. This differs from the assessment of yacht X where the life time is 50 years and maintenance was included.

This assessment gave not only results for each material group, which will be compared in the next paragraph, but also results per yacht system were given and shown in table 1.1. These results give an identification of the systems that are most interesting for further investigation. As expected from previous research on ships in general the impact from the hull and superstructure is one of the most significant. Besides steel Chatzinikolaou and Ventikos [18] had the hull protection considered in the framework, in the results the system of Insulation, paint and fairing is one of the systems with a large impact. However, what makes the assessment of a yacht interesting is that the impact from the interior and exterior is in the same order of magnitude as hull and superstructure.

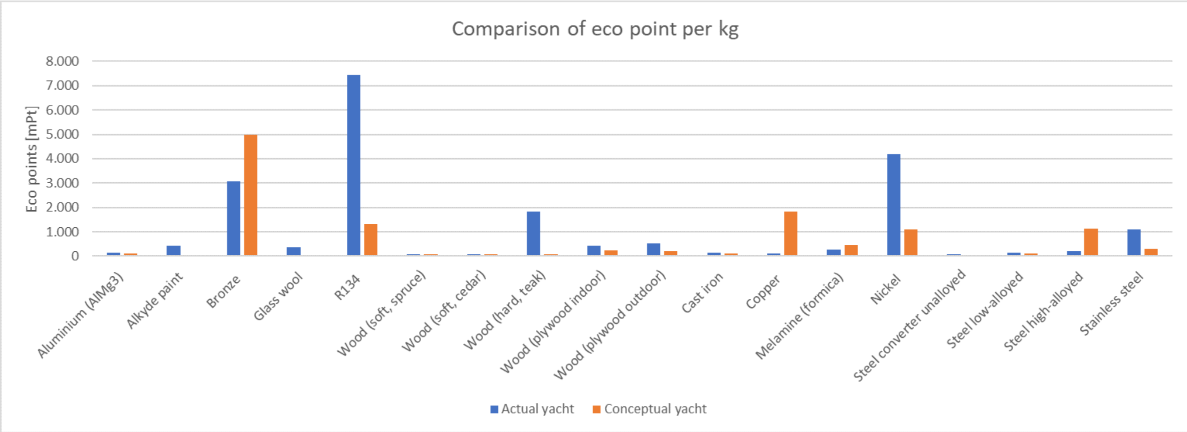
Yacht system	% weight	% impact [mPt]
01 - Hull	33.71%	15.89%
02 - Superstructure	12.50%	11.56%
03 - Engine room	8.00%	7.20%
04 - Propulsion	4.51%	7.64%
05 - Systems	5.37%	2.23%
06 - Electric	4.85%	3.63%
07 - Steering and mooring	2.10%	2.34%
08 - Air conditioning and ventilation	2.55%	1.46%
09 - Insulation, paint and fairing	7.03%	11.62%
10 - Interior	12.51%	18.01%
11 - Exterior	2.18%	13.43%
12 - Miscellaneous	4.68%	4.98%

Table 1.1: Impact of each yacht system

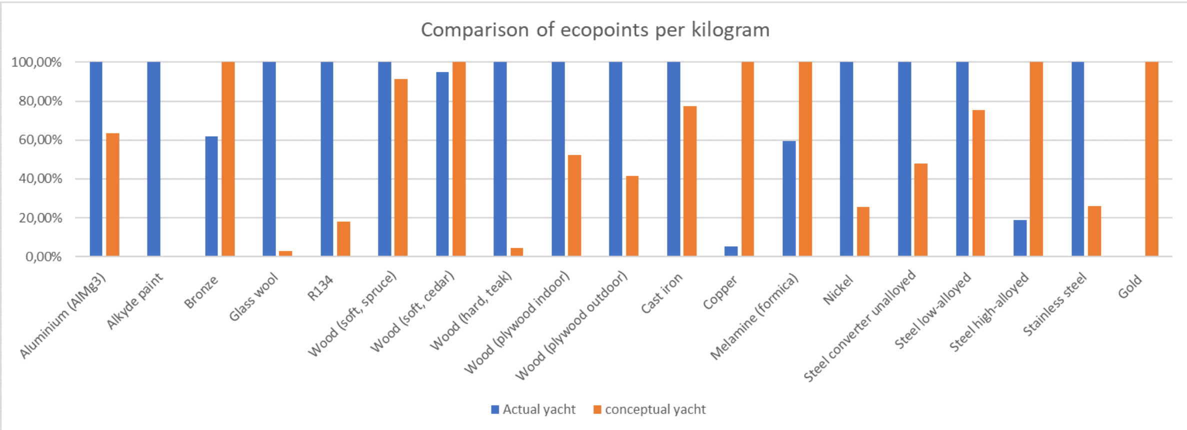
Comparison
A comparison is made between the assessments of the conceptual, yacht X, and actual yacht, yacht Y. A comparison is possible because of the similarities in size and the results are both in eco points. For both assessments it was possible to calculate the total weight and the eco points per material of each material that was used. This comparison shows three interesting results which will be discussed below.

The first interesting conclusion that can be drawn from the comparison is that the biggest part of the impact is caused by a limited number of materials. These materials either have a high number of eco points per kilogram of material (Bronze) or there is a lot of this material used(steel). The comparison allowed the formation of a list of 19 materials that all have an impact larger than 1% in either one of the assessments. If the requirement is set at a minimum of 2% of the total impact at minimally one of the assessments then the list of materials reduces to 14. There are only 8 materials that have an impact that is higher than 5%.
The 19 materials that all have a larger impact than 1% in either one of the assessments represent 95% of the total impact of the actual yacht and 78% of the total impact of the assessment of the concept yacht. Because the materials represent such a large part of the total impact further analysis is focused on these materials.

The text above very explicitly states that the impact should be bigger in **either** one of the assessments. This is done because the impact per materials varies significantly between the two assessments. This is the second interesting conclusion from the comparison. To illustrate this difference figure 1.4a shows the eco points per kilogram of material for both assessments. To better analyse this, these values have also been normalized which is shown in figure 1.4b and displays the relative differences between the assessments better. In this second figure it is clear that though both assessments have been done with the same method there is a big difference in the eco points per material, which is unexpected. As shortly said in the paragraph about eco points the weighing is partly based on social science and includes different cultural perspectives. In the assessment of yacht Y there is no reference to the precise weighing method used but for the assessment of the yacht X the Hierarchist perspective is used. This is the default method in LCA software [31, 52] and combines effects in the long and short term. Since this is the default setting it is probable that this is also used for the



(a) Comparison of the impact based on eco points between yachts X and Y

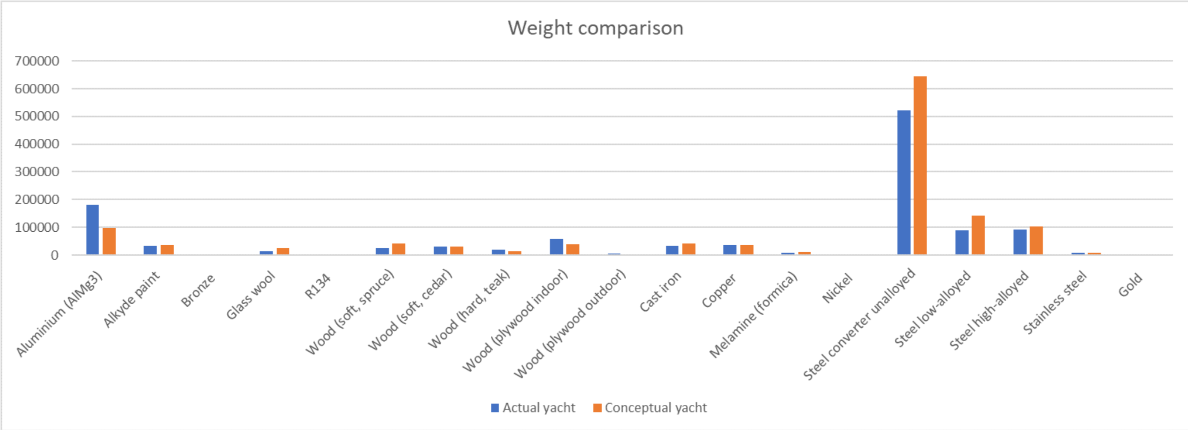


(b) Comparison of the relative impact between yachts X and Y

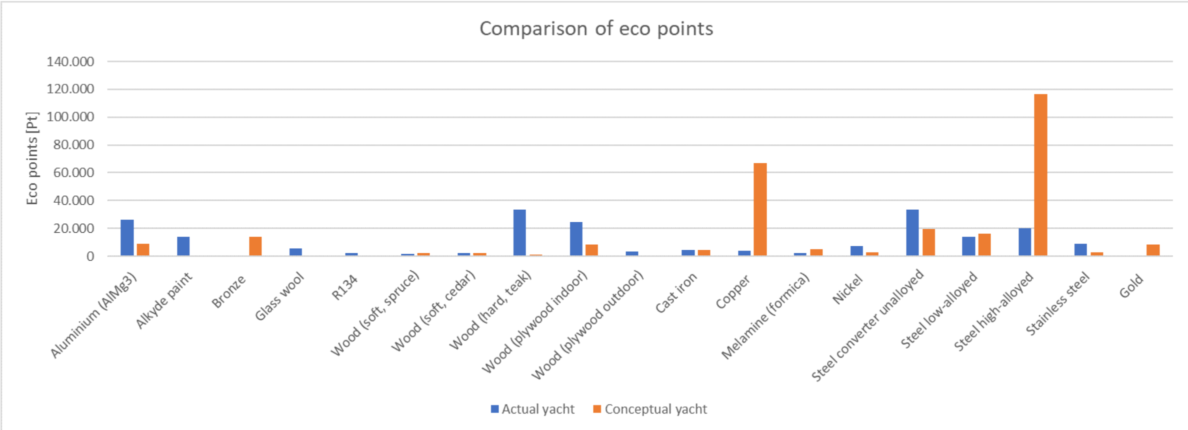
Figure 1.4: Comparison of impact per kg of material

assessment of the actual yacht.
More likely is that the variations are caused by the difference in the source of the data. The assessment of the concept yacht X is done with the ecoinvent database, a dedicated database, and for the yacht Y Ecolizer is used [49], this database gave eco points based on the Eco-indicator 99 method but nowadays has implemented a new method called Recipe. Ecolizer is a Belgian database and thus there is a possibility that localized information is used but this is not explicitly said. This comparison between the assessments clearly shows that not only the assessment method has to be the same but more details about the resources of information should be documented to allow for good comparison. This is important for the YETI as the main goal is comparison between yachts.

During the comparison not only the eco points per material are analysed but also the weight of the materials for both assessments. Therefore figure 1.5a first shows the comparison of the amount of each material that is used on board and figure 1.5b shows the total amount of eco points of each material. The differences in the weight per materials between the two assessments sometimes increases the differences but can also counteract the differences in eco points per kg.



(a) Comparison of the used materials based on their mass



(b) Comparison based on percentage

Figure 1.5: Comparison of the used materials on eco points

1.2.5. Conclusions from literature

The requirements for the YETI given in this chapter make it hard to find a methodology in the already existing research that is usable for the YETI. The research into environmental assessments done for ships in general shows that the LCA methodology is promising. The research of Chatzinikolaou and Ventikos gives interesting ideas about standardizing the components of a yacht that are taken into account in the environmental assessment. However, the research done at De Voogt internally indicates that the distribution of the components with a high environmental impact differs between yachts and ships in general. On the other hand, the research done for the Product Category Rules, that forms the basis for environmental product declarations, is focused on the yachts specifically. Yet this requires a much more detailed study of the yacht. Though the PCR is constructed to allow for comparison, it needs further definition to fulfill the YETI requirements.

For the YETI there is a need for a new model, combining the strengths of previous research and adapting them for the specific application. The creation of such a model can give more insights into the important aspects forming the environmental impact from yacht production. Besides, if compliant with the YETI requirements the model helps to make environmental assessments a regular practice in yachting.

1.3. Project description

The goal of this research is to develop a method to compare the impact of yacht production between different designs. This should result is a model that can be used for the calculation of the YETI score. Figure 1.6 shows the life of a yacht starting in the bottom left corner with the extraction of of raw materials. The life cycle follows that bold black line to the point were the yacht is delivered and operational. It goes on to the end of life moment of the yacht.
With documents signs it is indicated where information needs to be gathered that either influences the impact or the use of the yacht. Information needs to be gathered about:

1. Energy used for production
2. Materials used for production
3. Energy used for maintenance
4. Materials used for maintenance
5. Recycling rates of materials
6. Operational profile
7. Operational use of resources (Fuel)

Because of the focus for this thesis on the environmental impact from the production of the yacht, only the first five items will be included. To illustrate this, the intended system boundary for this thesis is shown in figure 1.6 by the green line. Because the operational use of the yacht is outside the scope of this thesis it is shown more simplified in the figure. Setting standards for the calculation of the environmental impact from the five items within the system's boundary should result in a framework that can be used for the comparison of yachts.
In the previous paragraphs of this chapter, different initiatives have been discussed that included a way of assessing the environmental impact from yacht or ship production. Due to the explicit requirements for the YETI it is not possible to use either of these initiatives. On the other hand, they provide insight in common used methods and materials that should be covered. Besides combining the strengths of these methodologies and adapting them to the YETI requirements ensures that the design of the model does not have to be made from scratch.
The creation of such a YETI model can help to get more insight in the important aspects of yacht, and ship, production when it comes to environmental impact. For the yachting industry these insight will help the industry to move towards a more sustainable future. Using the model will help yards and designers to know what they can already do to change the environmental impact from their yachts and where further research or innovation is required to reach the goal: a more sustainable yachting industry.

1.3.1. Research questions

As described in the project description, the aim of this research is to create a model for the yacht production part of the YETI. This aim translates into the following **main research question**:

> How can the environmental impact of yacht production be compared from a life cycle perspective?

To find the answer to the main question it is necessary to find the answers to different sub questions. The sub questions are based on the analysis of what should be defined clearly before the impact from yacht production can be calculated and compared. The **sub questions** are defined as follows:

1. What is the best way to apply LCA for the calculation of environmental impact from yacht production?
2. What are the life cycle stages of a yacht from a production perspective?
3. How can information on the yacht and its production process be measured and made transparent?
4. Are the results of the LCA influenced by design choices and boundary setting?

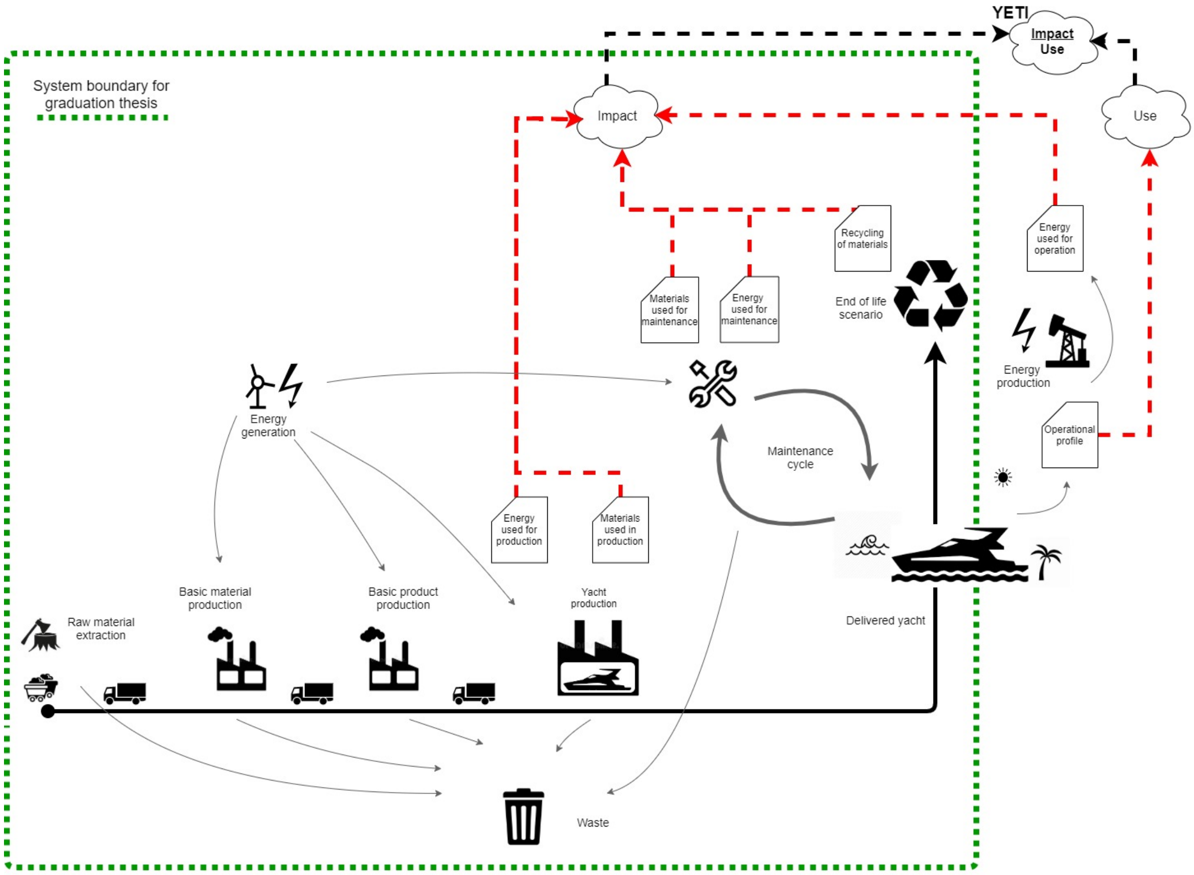


Figure 1.6: Overview of the things associated with the YETI score and the intended system boundary

1.3.2. Problem approach

This report aims to find the answer to the main research question as formulated above. As mentioned in the literature in paragraph 1.2, Life Cycle Assessment(LCA) is the methodology to perform environmental assessments from a life cycle perspective. As will be discussed in chapter 2 there are different ways to apply LCA. An analysis of the differences in the methodologies is performed and the best fit for the YETI is found in Fast Track LCA.

Before Fast Track LCA can be further defined for the application on a yacht the life cycle of the yacht in relation with production processes has to be determined. Over the different life phases building, maintenance and end of life a standard is created for the production life cycle in chapter 3. This life cycle is important as it creates an overview of the activities that can be taken into account for the YETI assessment.

Fast Track LCA is the chosen methodology but requires further definition to fulfill the requirements of the YETI and the application on a yacht. Chapter 4 gives the choices made in the five steps of the Fast Track LCA to create a standardized application of this method for the YETI. This includes choices on the system boundaries, the use of the ecoinvent database, life cycle inventory assessment method, LCA software and a standardized framework for the life cycle inventory that helps to gather all input data.

All the decisions made for Fast Track LCA are applied on a case study of a yacht that has been build by Feadship in recent years. Using this case study, chapter 5 consists of an analysis of the applicability of the methodology, the results obtained and a check to see if the results shows enough sensitivity with respect to design choices.

This research ends with chapter 6 that gives the answers on the sub questions and the main question. During the research different aspects were found that require more research than could be done in this thesis. This is written down in the recommendations.

2 Life Cycle Assessment

From the previous research about the impact of ships, as discussed in chapter 1, one method stands out when it comes to calculating the impact on the environment, this is the Life Cycle Assessment (LCA) method. This method can be applied to any product or service. Vogtländer [69] distinguishes two types of LCAs:

- The classical LCA ('full', 'rigorous') where every step is performed by the practitioner according to ISO 14040 and 14040 with a focus on calculation of the impact.
- The 'Fast Track' LCA where data stored in databases is used and the focus is on comparison of designs.

This chapter focuses on the differences between these two types of LCA in order to choose the right method to model the impact from yacht production for the YETI. After a short introduction of the method only the parts of the assessment where the difference is made for the YETI are further discussed. The chapter finishes with a comparison between the two methods.

2.1. ISO 14040 & 14044

The classical LCA as defined by the ISO in 14040 [39] and 14044 [48] is an in-depth assessment of the environmental impact of a product or service. The goal is the calculation of the environmental impact and in the standards it is highlighted that the results should not be used for the comparison [48]. The standard divides the LCA into four phases and information on each of these phases must be given. These phases are listed below.

1. The goal and scope definition phase
2. The life cycle inventory phase
3. The life cycle impact assessment phase
4. The interpretation phase

Only for the life cycle inventory and impact assessment phase a difference is made for the YETI. Therefore these will be discussed in more detail.

Life Cycle Inventory phase
The intent of the Life Cycle Inventory (LCI) is to collect data and calculation procedures to quantify all relevant inputs and outputs of a product system [39]. LCI is the phase of the LCA that takes the most of time and resources [2]. Though it seems to be described in ISO 14040 as three steps, namely data collection, data calculation and allocation, the further explanation in 14044 shows the full extend of this phase [48]. In reality this step requires a fully detailed analysis of every input and output flow of the system and not just a quantification.

Life Cycle Impact Assessment phase
In the Life Cycle Impact Assessment (LCIA) the link is made between the inventory data and the specific environmental impacts categories and their indicators. The LCIA consists of three phases:

3.1 Selection of impact categories, category indicators and characterization models.
3.2 Assignment of LCI results to the selected impact categories, for example linking different greenhouse gases to climate change. With each gas having its own Global Warming Potential. This step is called classification.
3.3 Calculation of category indicator results, this is called characterization.

There are also four optional steps of the LCIA which are shortly explained. The first optional step is **normalization**. Normalization means that the information of the magnitude of the category indicator is made relative to reference information like the global or national emissions. The second optional step is an extra **grouping** step which means that a sorting or ranking is applied to the impact categories. **Weighting** is the third optional step and is used to add up different indicator results, this has often not a fully scientific base but is also based on value choices. For this reason data from before weighting should be kept available as well. The last optional step is additional **data quality analysis** and gives the possibility to further investigate the results of the LCIA. Making use of either one of these steps depends on the aim of the research and how the data will be analysed.
The additional weighting step can be of interest when looking at the goal of the YETI, comparing different yachts. Weighting makes it possible to convert all results of impact categories to one single indicator. Though this is will not be a fully science based result, if the same weighing is used for the yachts they both contain the same assumptions and can thus be compared.

To perform the LCIA, standard assessment methods have been developed. A more extensive discussion on these methods will be given in paragraph 4.4.2.

2.2. Fast track LCA

Vogtländer [69] describes that the LCA as standardized by the ISO is needed when the environmental impact of a product has to be known from scratch. This means that all the complex processes included in the production have to be analyzed in detail. By using mass and energy balances these process have to be analyzed in order to know where to put system boundaries. The results of the LCIA should be analyzed per impact category, requiring in-depth knowledge of environmental science. Because this is not something anyone interested in LCA is capable of doing, Vogtländer proposes the Fast Track LCA. The goal is comparison of products and therefore a lot of simplifications can be made. The simplifications are in line with the ISO, which states that the choices you can make during the LCA should comply with the goal of the study [39].
For the Fast Track LCA the results of previous LCAs and the available information from environmental databases should be used. Vogtländer advises to make use of a single indicator which makes comparison and interpretation of the results a lot easier. The Fast Track LCA can be described by 5 different steps:

1. Establish the scope and goal of the analysis
2. Establish the system, functional unit and system boundaries
3. Quantify materials, use of energy, accuracy and allocation for the system
4. Enter the data into an Excel calculation sheet or a computer program
5. Interpret the results and draw conclusions

Even though the number of steps differs for the classical and the Fast Track LCA, the two methods are still closely related. The first two steps of Fast Track LCA are similar to the goal and scope definition phase of the classical LCA. The third step is similar to the Life Cycle Inventory phase and the fourth phase requires also a choice in LCIA method. Both methods end with a phase that interpreters the results in the for the method appropriate way.
To compare the Fast Track LCA steps with the activity's of the different phases described by the ISO, two main simplifications are made:

- Instead of going through all the LCI steps, the processes in the system are determined and data from databases is used to determine the impact from the process.

- The results are analyzed in terms of "This design performs better than the other one" and do not fully analyze the actual impact on the environment.

These simplifications reduce the amount of work to be performed and makes the LCA available for people who do not have a background as environmental scientist. Another advantage of the less extensive approach of Fast Track LCA is the possibility to apply it at the beginning of the design stage [69]. This is interesting for the YETI as designs can than be compared as well. Though keeping in mind that during the design stage the results will be less accurate.

2.3. Comparison of the methods

The two methods differ in the depth of research they require for the LCA. The differences that are important to create a model for the assessment of yacht production for the YETI are in two phases. First the LCI phase of the classical LCA and the quantification of materials and energy of the Fast Track LCA are further compared. Secondly the way LCIA are used in both methods is further analysed.

2.3.1. Comparison of the Life Cycle Inventory

Fast Track LCA has an advantage over the classical when it comes to the set up of the LCI. The standardization of the Fast Track LCA inventory is easier than for the classical LCA because it requires less in-depth information and more items can be predefined. Standardization is one of the requirements of the YETI as listed in paragraph 1.1.1. Furthermore, standardization of this inventory will make the model for the assessment of the environmental impact of yacht production comply with other requirements as well. The results will be more transparent as it will be known what is included and excluded for every assessment. Using Fast Track LCA makes creating the inventory easier for each assessment making it compliant with the requirement of the YETI design being as simple as possible. Looking at the Inventory of Hazardous Materials(IHM), every supplier has to specify if their products contain hazardous materials. It is not within the aim of the YETI that this should also be done for all materials contained in supplied products.

As information on every yacht will still have to be gathered the requirement for no manipulation is not yet met. How to meet this requirement is commented on in paragraph 4.5.

2.3.2. Comparison of the LCIA methods

Both methods have a different preference of the type of LCIA method that should be used. For the classical LCA midpoint indicators are preferred while Fast Track LCA prefers a single indicator method. First the difference between these method is explained in more detail. The difference has to do with the place on the impact pathway where the environmental impact is calculated. These different locations on the pathway are expressed in three different types of indicators that can be used by a LCIA method, namely: midpoint indicator, endpoint indicator and a single indicator. The impact pathway is shown in figure 2.1 where it can be seen that midpoint indicators are the first along this pathway. A mid point indicator should be chosen at the earliest point in the impact pathway after which the rest of the environmental processes are the same [59]. Examples of midpoint indicators are GWP(global warming potential), AP(acidification potential) and particulate matter. Midpoint indicators have an high accuracy but the impact of one midpoint can not be compared to that of an other. Because of the high accuracy midpoint indicator LCIA methods are advised for classical LCAs. Going further down the impact pathway it is possible to link these midpoint indicators to endpoints. End points indicators show how the different areas of protection are affected. These areas are human health, ecosystems and resource depletion. The uncertainties in the results increase further down the impact pathway. However, limiting the amount of indicators makes comparison of the LCA results easier.

Going even one step further it is possible to add together the total impact into one single score using a single indicator LCIA method. A single indicator is ideal for people without an environmental background who want to compare the impact from yachts. Detailed information on how different impact categories influence the single indicator is lost. But, the aim of the comparison becomes more clear: lowering the single score. This is the reason that Fast Track LCA, designed for comparison, argues to use a single indicator LCIA method when using the method.

2.3.3. Choice for LCA method

Fast Track LCA is chosen because of the use of a single score. This makes it more suitable for the comparison of different yacht designs, which is the goal of the YETI. Just as important is the simplification of the LCI phase. Simplifying this phase will make it easier for different companies to find the information needed for the LCI. Even though a simplified LCI can be used to determine a yacht's YETI score, it is important that a complete LCI is performed at some point in the design process of the YETI score to ensure that the environmental of all materials is evaluated. Otherwise it is possible that the YETI will miss materials embedded in the yacht that actually have a large environmental impact. Besides focusing on the creation of an easy to use

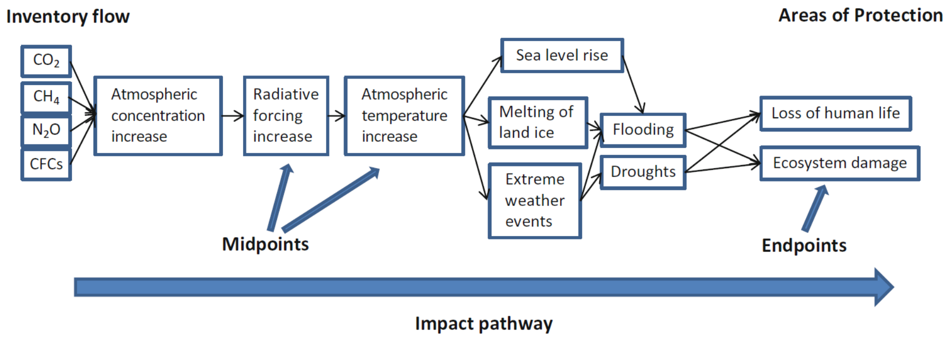


Figure 2.1: Simple impact pathway for climate change [59]

model for the assessment of the environmental impact, other research should also focus on an extensive LCI in order to make sure that no significant contributor is missed.

The choice for Fast Track LCA answers the second sub question of this research: "What is the best way to apply LCA for the calculation of environmental impact of yacht production?". But, it requires a bit more definition. The five steps that are part of the Fast Track LCA require more choices about the way that LCA is applied. For this reason these five steps will be discussed in more detail and the associated choices per step will be explained. Before the Fast Track LCA can be further determined it is important to define the life cycle of a yacht.

3
Production Life Cycle

That the activities on the yard should be included in an assessment of environmental impact caused by the production of a luxury yacht will seem logical. But there are far more activities that can be considered as part of the production of a yacht. These are mostly activities that take place in order to get the required resources available on the yard, such as resources depletion, transportation and production of semi finished products. When looking at production, it could be described in the most basic form as using energy to put materials together. The effect of using materials depends on the time for which the material is used and what is done with it afterwards. For this reason maintenance, refits and the "end of life" scenario are important phases for the assessment of yacht production. In this chapter all important activities of the different life phases are discussed. A life cycle will be created but it needs to be standardized for the use in the YETI. Therefore considerations are also given on activities that can be included of excluded in the YETI assessment.

3.1. Building

The processes for building a yacht are mostly similar at different yards and can generally be described by the following steps [55, 68]:

1. Pre-fabrication - During this phase plates and profiles are already put together into panels.
2. Section building - Different panels are put together into pre-assembled block section. These section are already provided with equipment piping, this is called pre-outfitting.
3. Assembly of the hull - All the block sections are joint together.
4. Final outfitting - During the outfitting the interior and exterior installed and all the systems are made ready. For yachts this phase takes considerable longer since there is much more interior work.
5. Launch - The launch can sometimes be before the outfitting is done, the rest of the outfitting is then done when the ship is along the quay.
6. Sea trials - The sea trials mark the end of the production and the hand over to the client.

Though for every ship the production process is similar, there is a big difference with respect to where the activities take place. For all shipyards(for shipping- and working- vessels as for yachts) there is difference on the level of work that is done by the yard it self. Nowadays lots of yards are becoming assembly places, meaning they integrate the parts that are build by subcontractors instead of producing everything themselves. This high level of subcontracting is implemented because it has a positive effect on the lead time [55]. This results in a wide spread in possible activities on the yard: "The production depth of every yard is different. While yards that do everything in-house still exist, the other extreme, where the yard only facilitates the building of the vessel, also exist" [56].

This difference is important in the assessment of yacht production, because it raises the question of what needs to be considered as the yacht production process and where the impact should be allocated. Is a yard that buys its hull and superstructure from a supplier or subcontractor assessed in the same manner as a yard that builds in-house? These differences require strict boundary setting in order to ensure that comparison between yachts that are built on different yards is possible.

When analysing this difference in the yacht building industry it can be seen that it indeed is a relevant matter. For example for the structure (hull and superstructure) there are three different ways seen in The Netherlands. Royal Huisman builds their own structure, De Vries and Amels build their structure at a daughter company and Van Lent and Oceanco build at an external company. Furthermore, interior and electrical systems are also often produced by a subcontractor.
The use of subcontractors has a large influence on the information that is available about the production processes. The yard does have the information on what is placed on the yacht but not how this was produced. This means that because of subcontracting it is not possible to compare yards with each other, but only the products. To give an example, a yard that produces the structure itself has a much larger energy bill than a yard which subcontracts this work.

Chapter 1 described that the aim of this research was to assess the environmental impact of the production of a yacht. Figure 1.6 shows that the system boundaries include energy use, transport, waste and the yard processes. However, due to the different levels of subcontracting comparison of assessments including all these building factors is not possible within the requirements of the YETI. Data can always be gathered but the question is how much effort can data gathering require? The only way to compare yacht production including all these factors (energy use, transport, waste and the yard processes) is if the YETI assessments included this information on every item on board the yacht. With a yard having hundreds of different suppliers this would require an enormous amount of work. This would be conflicting with the requirement of the YETI assessment being as simple as possible. Including energy use, transport, waste and the yard processes for only specific items of the yacht gives designers and yards the possibility to relocate polluting processes outside of the system boundaries while for others they would be included. Leading to a method that is unsuited for comparison. This means that the system boundaries have to be adjusted to exclude energy use, transport, waste and the yard processes. What is left are the materials and items that end up on board the yacht. Figure 3.1 shows what the system boundaries look like if the assessment only accounts for the materials and items that end up on board. Resetting the system boundaries it is likely that a large part of the impact is excluded. The problem is that it is not known how large this underestimation of the impact will be. In the assessment done for yacht X (paragraph 1.2.4) the energy accounted for 10% of the total impact and it is likely that this will be one of the biggest under estimations with the restricted system boundaries. Resetting the system boundaries has another disadvantage, only taking into account the materials that end up on board the yacht means that it is more an assessment of the design than the production process. Meaning that the YETI score only assessed the designer and not the yard as the yard can barely influence the result.

For the YETI there is a need for a standardized production life cycle in order to make fair and transparent comparisons between yachts. This means that in the model created using Fast Track LCA in chapter 4 only contains the information on the materials and products that end up on board the yacht. Every YETI assessment will underestimate the environmental impact in the same manner. Making lowering the impact form yacht production seem even less important than lowering the operational environmental impact. In order to get some idea of the underestimation that is made, part of the sensitivity check in chapter 5 is to investigate the extra impact created by including the used energy.

As will be explained explained in paragraph 4.4.1, the ecoinvent database is used to link the materials that are used to the impact they have on the environment. The ecoinvent database contains information from raw material(or resource) extraction up to basic material production. This includes the global average information on the transport that is required to the location of the basic material production. However for some materials, such as batteries, the production of the battery is also contained in the database. Though the basic product production is excluded in general, if no better information is available this should be used, as is the case for batteries. Transportation to the yard is excluded because the research on the actual yacht discussed in paragraph 1.2.4 the transport of materials was 1.81% of the total impact and therefore set outside of the system boundary. The energy used in production is calculated in that research at 9.88%, since this contribution is much larger it would be more interesting to put effort in finding a way to implement energy use on the yard.

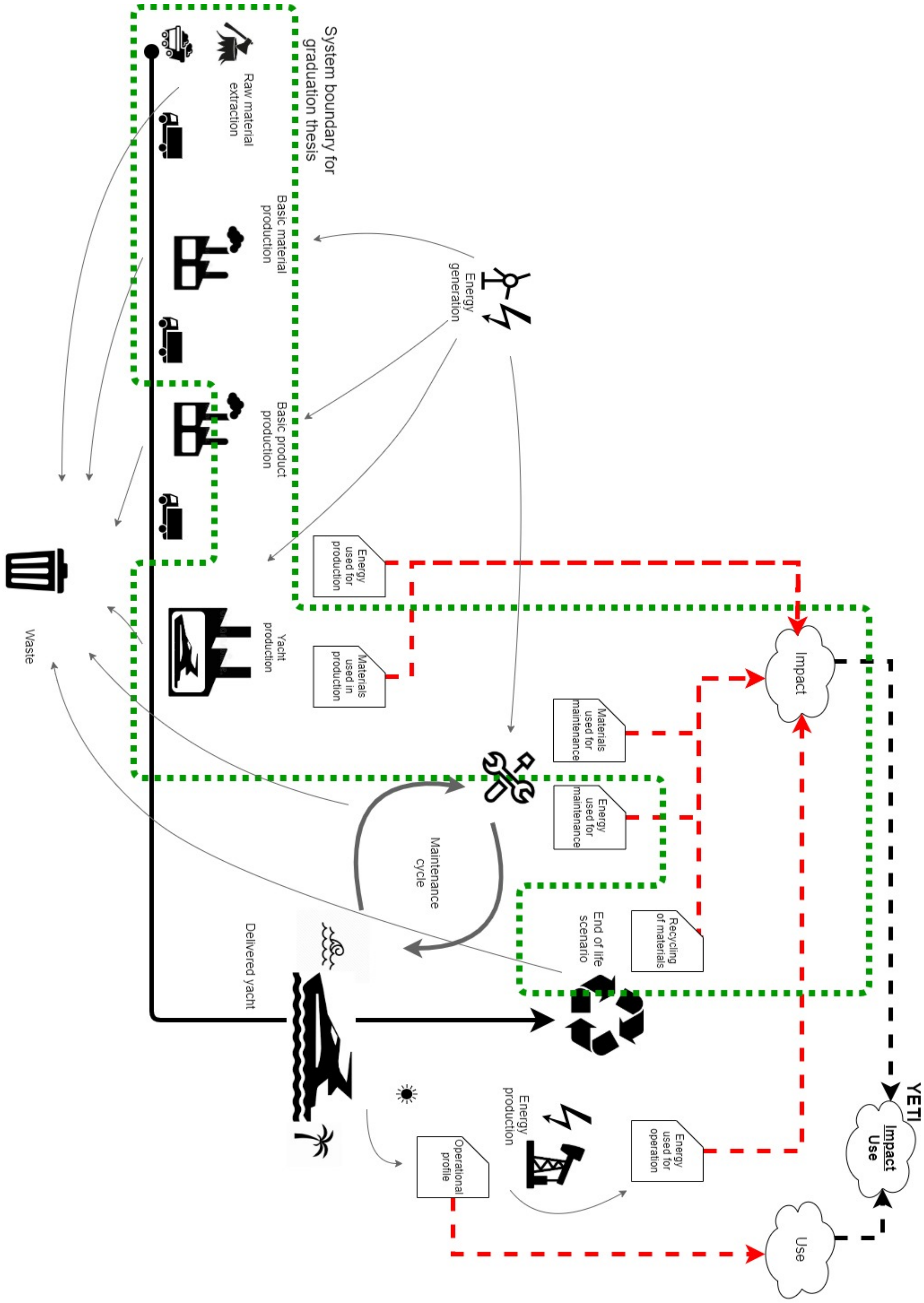


Figure 3.1: Adjusted system boundaries

3.2. Maintenance

The maintenance on the yacht is also considered in the production life cycle and consists of two components, namely the maintenance required by the classification society and maintenance that is required to maintain the super yacht standard.

Maintenance that has to be done according to the classification society is based on surveys. Over the life time of the yacht it has to undergo different surveys in order to remain certified. Based on the Lloyds rules [45] Feadship has made a Survey Cycle which is shown in figure 3.2. The different types of surveys have different time lines but all come together for the special survey each five years. The yacht will be re-certified during its special survey.

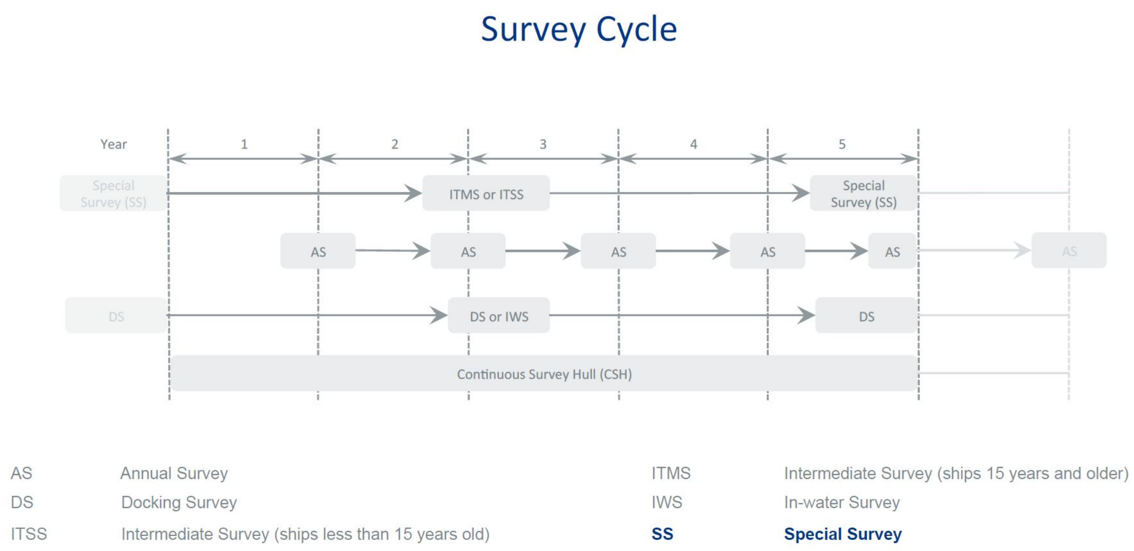


Figure 3.2: Survey cycle of a Feadship yacht [23]

Annual Surveys (AS) have to be done every year and consist of only visual inspection and can all be done on board. One of the yacht's captains indicated that this visual inspection normally does not result in any additional maintenance. For these reasons it is assumed that this will not require any effort associated with material use or energy.

Intermediate surveys are held every 2 or 3 years, so mostly every 2.5 years, and can replace the annual survey of that year. "The intermediate survey should be an inspection of items relevant to the particular certificate to ensure that they are in a satisfactory condition and are fit for the service for which the ship is intended" [45]. On the same timeline as intermediate surveys are the docking surveys or, as it is called by Lloyds Register, "inspection to the outside of the ship's bottom of cargo ships". This survey normally takes place in a dry dock. Due to the similar timelines the intermediate and docking survey are often combined.

The special survey is the renewal survey which has to take place 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 [45]". Though the inspection specifies a list of systems to be checked, the conversations with captains and employees from the Feadship refit department indicated that there is not a specific list of systems that actually need to have parts replaced.

The surveys imposed by the classification society ensure two moments every five years that the yacht has to go into a dock, every 2.5 years. Because the yacht is already in the dock other maintenance is planned during these docking moments. From different conversations within the Yacht Services and Refit department of Feadship and a conversation with a captain, the following regular maintenance scheme for these docking moments is established. They all highlighted that the maintenance done is mostly based on the budget the owner wants to spend and how the yacht is used. Therefore multiple conversations were held and only the activities over which agreement was reached and that were quantifiable are listed below. The maintenance that is done every 2.5 years:

- Cleaning the underwater ship
- Painting the underwater ship
- Replacing sacrificial anodes

Every 5 years the maintenance consists of all the activity's of the 2.5 year maintenance plus:

- Full paint job of the yacht

3.3. Refit and end of life

In yachting the term refit is used when not only the necessary maintenance is done but also the interior, exterior or ship systems are adjusted or upgraded. While maintenance ensures the yacht is operable and safe, refits are done for the luxury experience and the pleasure of the owner. For this reason, the amount of refits and the work done during a refit depends on the budget given by the owner. In order to say something about the refits, data is analyzed from both Super Yacht Times and the Super Yacht Group and the information from conversations within the Yacht Refit and Services department of Feadship is considered. All highlight that no two refits are the same. Depending on many parameters including operational budget, operational profile but mostly the owners wishes, the refits schedule can vary from more smaller refits every few years to only one of two major refits in a longer time period.

Docking time is always a factor that has to be reduced as it costs money and during that time the owner can not use the yacht. For this reason refits are commonly scheduled at the same time as the mandatory surveys for the classification society (Appendix B). This results in very small refits done almost every time a yacht goes into a dock, which are more upgrades of the same interior . A smaller refit can mean replacing the electronics for the owner or replacing small items in the interior. Data that describes the activities per docking is unfortunately not available, which makes it difficult to determine an interval for these activities. However, both Super Yacht Times and Peter Schoneveld (Feadship services Appendix B) agreed that the painting activities are always combined with the surveys. Every 2.5 years the underwater ship gets cleaned, painted and protected against corrosion. Every 5 years the whole ship is painted in addition to the underwater ship. Further activities during these docking periods are too much at random to distinguish.

As mentioned, during the surveys smaller refits take place but it is also seen that yachts get an extensive refit. Again the following information is based on experience and can very a lot per yacht but Schoneveld indicated that every 15-20 years a larger refit is required. Some of the equipment on board has reached its lifespan or the implementation of new technology requires changes to the electric infrastructure of the yacht. For example, changing to LED lights requires redoing the entire cabling of the yacht due to a change in frequency. Major refits therefore take much more time then just the added time to the docking period for painting.

Since direct information about refits is scarce the docking time is analyzed. To find out when larger refits take place it is assumed, and checked with Super Yacht Times and the Feadship services department, that major refits take more than a year. Starting from 2016, Super Yacht Times has been keeping track of the dockings that take place, listing the ship's details and the time a yacht has been in a dock. Since then 2112 dockings have been registered by Super Yacht Times. The yachts are divided into age groups of 5 years and figure 3.3 shows how this data translates to those age groups.

Remarkable is the peak for refits that have a duration of 5 to 6 months. This is due to the mandatory docking every five years, during which the whole yacht is painted. Painting the entire yacht normally takes about 5 to 6 months. The only other noticeable difference is that yachts with an age between 0-5 years have a relatively large amount of 1 month docking periods, probably this is because of warranty activities. Looking at refits with a duration of more than 1 year the 25+ years old yachts have the highest percentage. Of the 25+ years old yachts 2.6% was docked longer than a year. How these docking are divided over the different age groups is shown in figure 3.4. Of these recorded docking periods longer than a year, 54% was from a yacht older than 25+ years. However, since 2016 Super Yacht Times has only documented 13 yachts that were docked longer than 1 year (against the total of 2112 docked yachts in counted in total). More data is necessary to validate

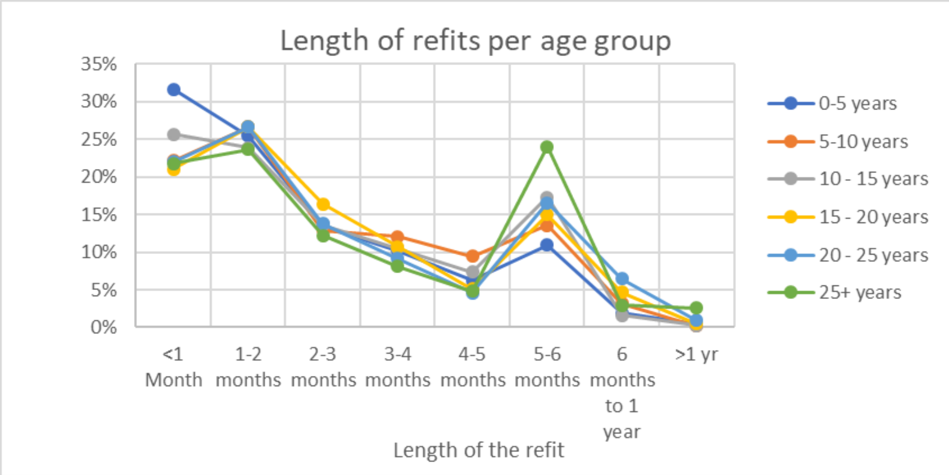


Figure 3.3: Data of the duration of docking periods per age group of yachts [63]

the these numbers.

Other information from Super Yacht Times shows that of all the refits taken place in 2016, 2017 and 2018 the amount of refits represented by yachts older than 20 years is 17.2%, 19.1% and 20.1% respectively. But the fleet of yachts more than 20 years old is 33% of the entire active fleet. Showing that investing in the yacht, by maintaining it, is only done by 2/3 of this group of yachts, giving some indication that these yachts might have reached their economic life time.

To get a clearer picture of the balance between refits and the end of life moment of a yacht the value of yachts is also examined. By looking at the resale prices of motor yachts of different delivery years, the depreciation of yachts can be considered. Together with Super Yacht Times the information of the second hand price per age group is determined. In figure 3.5 the light grey line shows the average sales prices of yachts for sale against the age in an age group, so 2.5 is taken for the group with an age between 0 and 5. This line contains information on motor yachts for sale with a length of more than 40 meters and is based on data from 220 yachts in total. The data on yachts between 16 and 40 year old is only 30%, so information on this group is limited.

Since Feadship is at the top of the market, the publicly available information on the Super Yacht Times website is used to see how the more luxurious brands perform with respect to the market average. This is shown by the colored dots in figure 3.5 per brand. The prices of the more luxurious brands lie above the total market average.

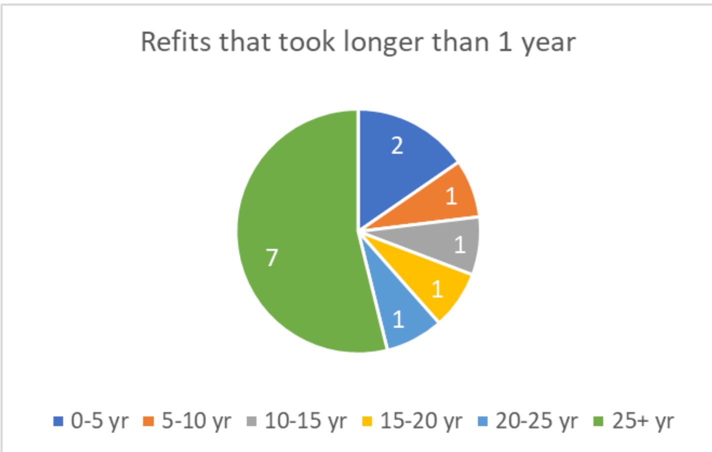


Figure 3.4: Insight in the refits that took longer than one year [63]

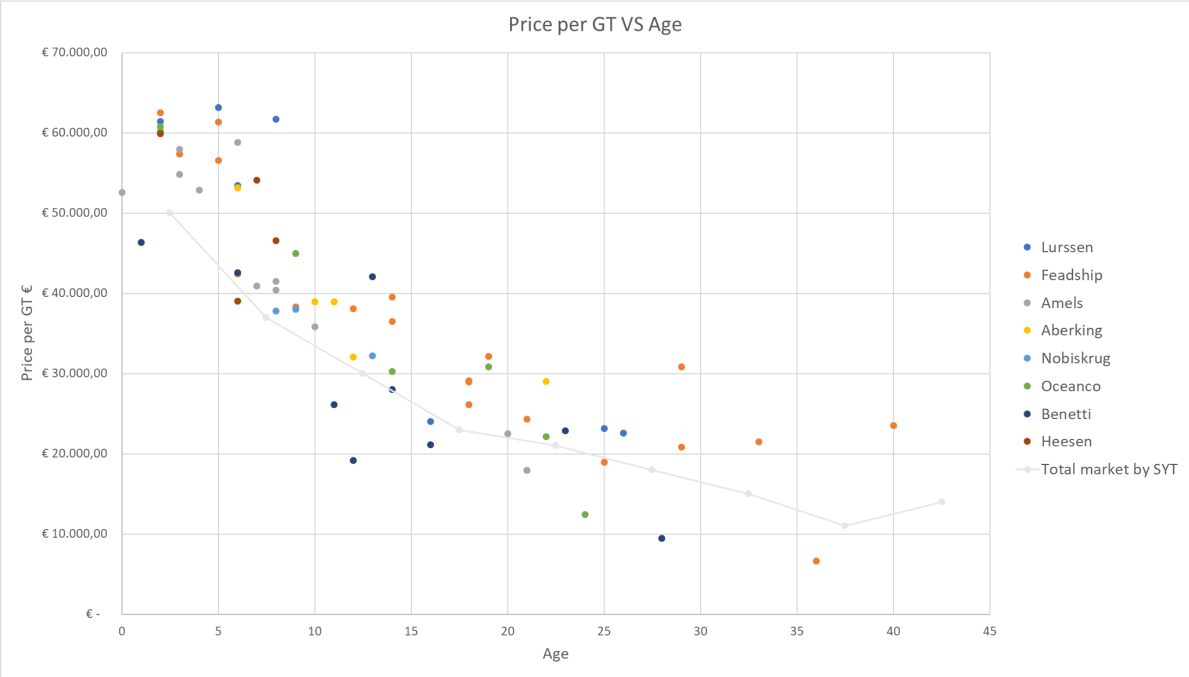


Figure 3.5: Depreciation of yachts [5, 63]

The trend that both the total market data and the data from the more luxurious brands show is that they both seem to reach an asymptote. For the total market this seems to be about €14.000 per GT for yachts older than 30 years based on the information from Super Yacht Times. For the more luxurious yachts this asymptote seems to be more in the direction of €20.000 and it seems to be reached between 20 and 25 years.

While having conversations about refits the question was also raised when a refit is more a rebuild. This would be the case when so much is changed that almost everything, except for the hull and some machinery, is replaced. With this amount of work and changes it is possible to see it as a brand new yacht. This is often the case when refits are done for yachts having an age of 20 years. Technology has changed so much that when you install the latest technology you have to change everything because it will interfere with each other (Appendix B). Since this also seems to coincide with the data about the depreciation of yachts after 20 years, the end of life of yacht is modeled at 20 years. This is done instead of modelling a refit after 20 years and taking a longer life time. After 20 years the main construction and machinery can be reused and is thus fully recycled. The other parts are scrapped.

3.4. Life cycle of a yacht

The result from the discussion in this chapter is the yacht life cycle as displayed in figure 3.6. For the YETI this life cycle can not contain detailed information on the basic product production and the yacht production because the different levels of subcontracting make these steps not comparable. The result is that the use of energy, transport, waste and the yard processes are excluded from the standard life cycle for the assessment. The total life cycle of the yacht is taken at the time needed for the build phase and 20 years of operational use. At 20 years an extensive refit is needed and a yacht seems to reach it's economic end of life as well. With this life cycle the first sub question of this research "What are the life cycle stages of a yacht from a production perspective?" is answered.

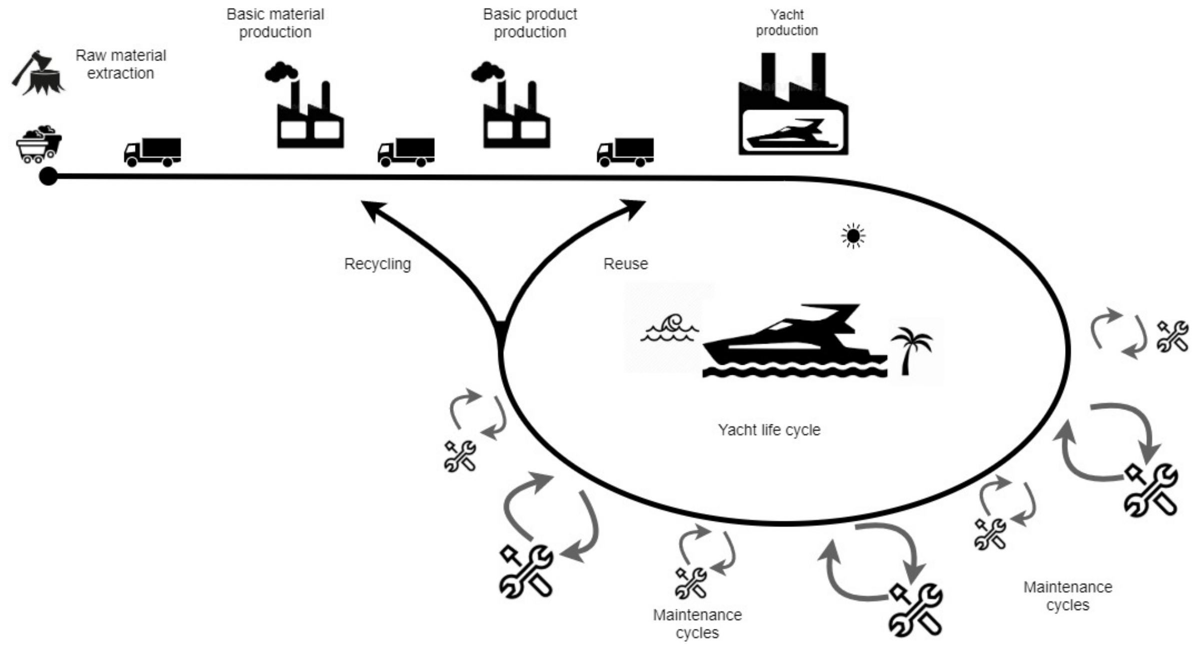


Figure 3.6: Production life cycle of yacht

4

Application of Fast Track LCA

Now that the LCA methodology is chosen and the production life cycle for yachts is determined, further implementation of the Fast Track LCA is possible. Fast Track LCA is a LCA method containing five steps, and to comply with the YETI these five steps all need standardization. How the Fast Track LCA method is standardized for the application on the production life cycle of a yacht is explained in this chapter.

4.1. Step 1: Goal and scope definition

The goal and scope definition is the first step of any LCA. During the rest of the LCA choices have to be made on system boundaries, functional unit, inventory depth and inventory assessment methodology (all explained in this chapter) and the ISO requires these choices to be in line with the goal and scope of the assessment [39]. For the model the goal and scope are linked to the goal of the YETI and the scope of this research to look at the impact from yacht production.

4.1.1. Scope

This research is scoped to investigate the possibility to create a simple methodology to compare the impact from the production of different yachts. Environmental impact from a yacht can be linked to either the production of the yacht or its operational use, and these two vary significant. In general this is because the materials and energy used for the production of the yacht are linked to the design and yard processes. Therefore this part of the impact is linked to the yard parameters and parameters of the yacht defining its size. On the other hand the impact from operational use is dominated by the emissions caused by the energy generation on board. These are linked to functions of the yacht such as hotel load and speed.

This thesis focuses on finding a methodology for the comparison of the production related activities of a yacht. This choice is made due to time limitations for this research and the possibility to easily separate the operational use and production. The different life phases that contain activities that can be linked to production are discussed in in chapter 3 and will be part of the scope of this research.

4.1.2. Goal

The goal of the YETI is to push the yachting industry towards a more sustainable future. The idea is to do this by comparing the impact of the yachts, expressed in the YETI score. The goal of this research is to create a model to calculate the environmental impact from yacht production in a way that allows for comparison. In this model the requirements of paragraph 1.1 are leading for design choices within the model. Since the choices in this model should reflect these requirements of the YETI, they are listed below:

1. The calculation method should be transparent
2. The YETI should remain as simple as possible for both understandability and minimizing the effort for calculation
3. Design of the YETI should be in such a way that manipulation is not possible.
4. Results should be obtained through standardized processes and data has to be verified through standardized methods.
5. The YETI should be designed for comparison

4.1.3. Case

In order to create the model for the calculation of the production related part of the YETI, information from a yacht build by Feadship is used, named yacht A in this research. The yacht has been built in the last couple of years. The yacht has been chosen because it is representative of the yachts built by Feadship. Furthermore the construction was finished by the time this research started which is considered a benefit with respect to data availability. Specific information on this yacht can be found in appendix A. The use of this case for the creation of the model has benefits when it comes to gathering information on the production process. However, it has some drawbacks. Gathered information and solutions are now based on the design data of yacht A and thus they do not necessarily represent the true information for the entire fleet of yachts. Though the model is created in such a way that it can be used for different yachts, some predefined choices will have to validated with data from other yachts.

4.2. Step 2: Define the system, functional unit and system boundaries

Especially when comparing yachts, it is important to clearly define the system, the functional unit and the system boundaries. These topics will be discussed separately in the following paragraphs.

4.2.1. The system

The product under investigation is a yacht, either for private use or for commercial operation but it does not carry cargo. The yacht should have at least the following characteristics:

- Non shipping vessel
- Designed for the pleasure of the owner/customer
- Crewed year round
- Can make the Atlantic crossing on it's own.

4.2.2. The functional unit

The functional unit defines the quantification of the identified functions of the product that is under study [39]. As said the function of a yacht is to provide luxury for the owner, which is a hard function to quantify. This means that another functional unit will have to be chosen based on a yacht parameter. A requirement for this parameter is that is can be linked to both production and operational use of the yacht. Based on this requirement different options for the functional unit will be discussed in this paragraph.

For the production of a yacht a functional unit can be defined based on the product, the yacht, or the producer, the yard. Using a parameter that describes the yard's efficiency, in terms of environmental impact, is not desirable because the goal for the YETI is to compare yachts and not yards. A yacht parameter that is frequently used to indicate ship size is gross tonnage(GT). This parameter is an indirect measure of internal volume of a ship. For the YETI cubic meters of luxury interior is proposed as it combines the function of providing luxury to a ship parameter. Information of the yacht is available per yacht and this data should thus be divided by the chosen ship parameter, either total GT or cubic meters interior.

Another option would be to use a parameter based on the operational profile of a yacht. Functional units based on the operational use of a yacht could be the impact per nautical mile (based on the expression used by the EEDI [46]) or the transport of one paying passenger(either the owner or tenant) for one hour of use [17]. Both are easily linked to the operational use of the yacht and thus its operational profile. However, the definition of such a standardized operational profile is the topic of a lot of discussion within the Joint Industry Project concerned with the creation of the YETI [7, 8]. The definition of such an operational profile will most likely be done in the future, making it possible to compare on a parameter linked to the operational use of the yacht. This means that the impact from the production of the yacht will have to be linked to the operational use. This is most easily done by dividing the total impact of yacht production over its life time. Meaning that first the total impact of the yacht has to be calculated. As long as the discussion on the operational profile is not concluded, using the production of 1 yacht as functional unit provides the most flexibility to transform it to any functional unit that will be used for both the production and operational use.

The main difficulty for the choice of the functional unit is the uncertainty for the choice within the entire YETI Joint Industry Project. Using one yacht as a functional unit for the framework for the impact of the production has the main advantage of flexibility and data is already available per yacht. For this reason the **one**

yacht is chosen as the functional unit for the framework.

4.2.3. The system boundaries

Setting clear system boundaries has to be done to ensure that the same is contained in every comparison based on the YETI score. The system boundaries have to be created in such a way that it is possible for all yacht builders to gather the information with in the boundaries. For this reason the system boundaries have a strong connection to the differences in building processes, but also to the maintenance done and the end of life to be included which are discussed in chapter 3. There are four different types of system boundaries that can be defined:

- General system boundaries
- Building system boundaries
- Maintenance system boundaries
- End of life system boundaries

These different types of system boundaries will be discussed in this paragraph. Besides these system boundaries a cut off criteria is often defined for life cycle assessments. This criteria is discussed at the end of this paragraph.

General system boundaries

General system boundaries for this research are system boundaries that are independent of the life phases. To create the system boundaries Product Category Rules (PCR) are analysed. There already is a PCR for yachts but the system boundaries are not taken from this PCR as the YETI has some specific requirements. Especially the requirements to design for comparison and to keep calculation simple translates in the exclusion of processes linked to the production of yachts. Besides the PCR for yachts a general frame work for the transport equipment is analyzed together with the PCR for airplanes. These are analysed because though it is not the main function of yacht, they are designed for the accommodation and transport of passengers. As accommodation is an important function as well the PCR for buildings is analysed in addition. The resulting system boundaries from the analysis of different PCRs are shown in table 4.1 and the analysis can be found in appendix F.

As explained in the scope of this chapter the focus of the model created in this research focuses on the production of the yacht. Therefore the life time operational use of the yacht is excluded but also the impact from any equipment, transportation or facility that is used for the production is excluded. Life cycles of used equipment, facilities and transportation are more indirect linked to production than materials and energy as production is the use of energy and materials to create product. During the operational use of the yacht different products are needed such as food, drinks and towels. Though these products require production they are excluded as they depend of the operational use of these products during the operational phase of the yacht. The production of the tenders and toys etc is excluded as these are highly complicated products, they are designed and produced outside the yard and are not part of any ship system.

	System boundary
Included	Yacht production*
Included	Maintenance work on the yacht*
Included	End of life scenario*
Excluded	Life time operational use of the yacht
Excluded	Life cycle of any equipment, transportation or production facility
Excluded	Production of standard items for the commercial operation of the product (food, towels, toiletry but also tenders and toys)
Excluded	Sea trials
Excluded	Any impact caused by employees(waste, traveling and office activities)
Location	Global

Table 4.1: General system boundaries.
*More details are given further in this paragraph

Building system boundaries
In paragraph 3.1 a discussion is held to determine what can be considered to be part of the building life phase of the yacht. It was concluded that due to different levels of subcontracting between different yards it is not possible to compare yachts including the impact caused by processes on the yard and the required energy. This results in the system boundaries as given in table 4.2. Limiting the system boundaries to raw material extraction and basic product production creates an underestimation of the total environmental impact. For the YETI this results in a model that only assesses the design and not the production process.

	System boundary
Included	Raw resource/materials extraction
Included	Basic product production
Excluded	Energy used at yard
Excluded	Water and gas consumed at the yard
Excluded	Processes at the yard
Excluded	Transport of materials to the yard
Excluded	Transport of materials on the yard
Excluded	Production and use of material for packaging

Table 4.2: System boundaries for the construction of the yacht

Maintenance system boundaries
In paragraph 3.2 the maintenance scheme for yachts has been determined. The regular maintenance focuses on the paint jobs and the protection of the hull. For maintenance only the materials used are considered to be in line with the system boundaries of the building phase. This translates into the system boundaries as given in table 4.3

	System boundary
Included	Raw resource/materials extraction
Included	Basic product production
Included	Paint jobs every 2.5 and 5 years
Excluded	Energy used during maintenance
Excluded	Processes during maintenance
Excluded	Transport of materials to maintenance location

Table 4.3: System boundaries for the maintenance phase of a yacht

End of life system boundaries
The end of life scenario is described in paragraph 3.3 and includes the recycling and reuse of materials. It translates in system boundaries for the end of life of the yacht as given in table 4.4. Including both reuse and recycling of the materials decreases the total impact from yacht production further. How this is implemented in the model and the effect of the model design choices will be discussed in paragraph 4.3.4.

	System boundary
Include	Reuse of structure and main machinery
Include	Impact reduction due metals that can be recycled
Exclude	Impact from recycling process.
Exclude	Transport related to recycling

Table 4.4: System boundaries for the end of life of a yacht

Resulting system boundaries
The new system boundaries for the YETI assessment of yacht production vary significantly from the system boundaries given in chapter 1, figure 1.6. Putting the new system boundaries in the same picture results in figure 4.1.

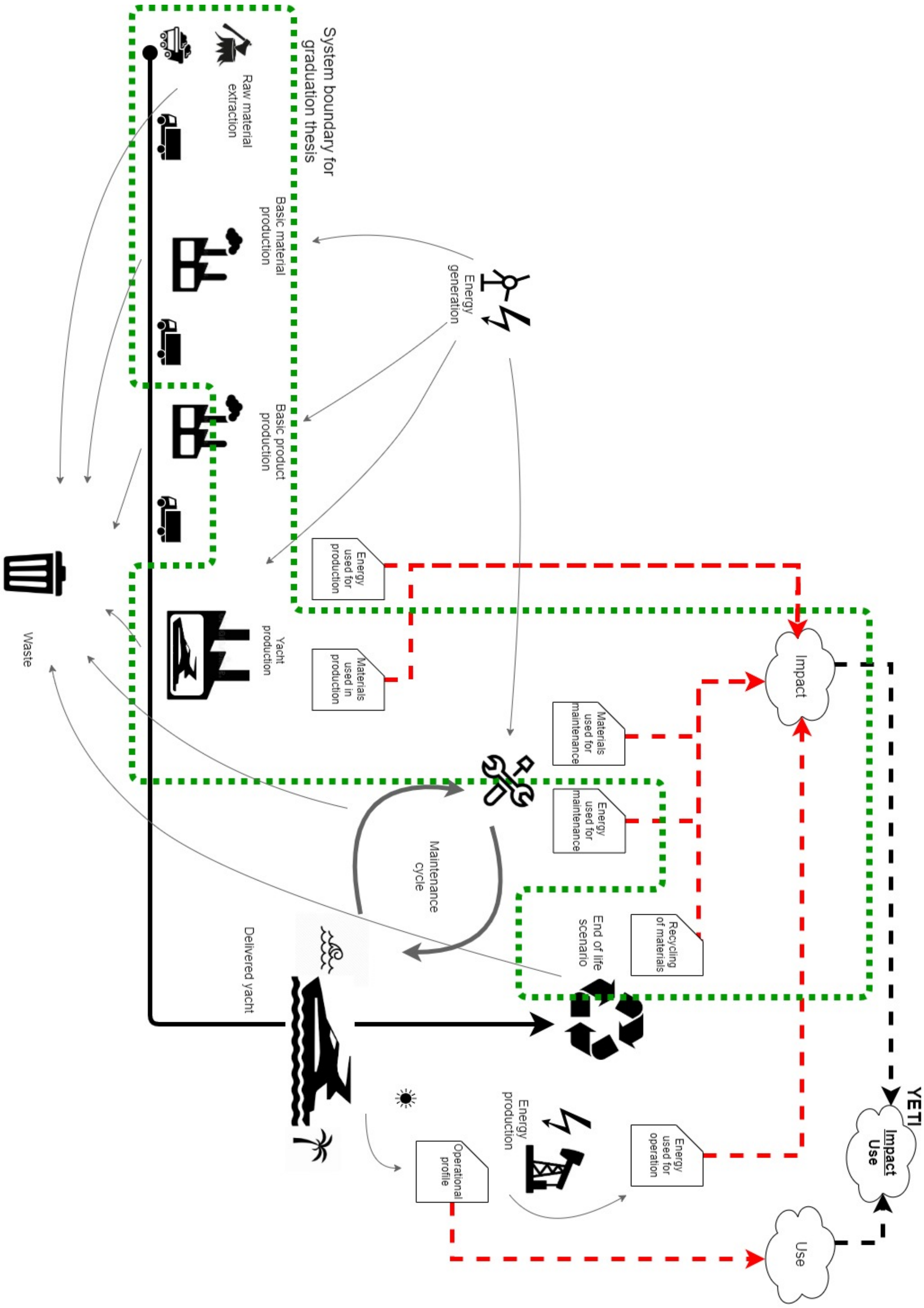


Figure 4.1: Adjusted system boundaries based on chapter 3

Cut off criteria

Another system boundary is the cut off criteria, it indicates the level of detail that is required for the assessment. In the assessments done by De Voogt into the environmental impact of yachts X and Y it became clear that there are a few materials that represent the larger part of the weight of the vessels and also the larger part of the impact, namely 19 materials that cover 78% and 95% of the total impact. For this reason the cut off criteria is set relatively low at 75% of the weight of the vessel. In the PCR the cut of criteria is set at 99% of the weight of the yacht [17]. Complying with this cut off criteria requires very detailed information on all systems on board the yacht. This more detailed research on what is on board the yacht is in line with the full LCA according to the ISO standards. For the YETI the aim is not an in depth research of every yacht but an easy to use methodology for the comparison of yachts. For this reason a much lower cut off criteria can be chosen. The chosen cut off criteria for the YETI is 75%.

4.3. Step 3: Quantify materials

This research focuses on the creation of a model for the calculation of the environmental impact from yacht production that can be used for comparison. There are three requirements of the YETI that can be solved by standardizing the quantification of the used materials. In order to compare yachts the same parts of the yachts should be included which is done by setting the system boundaries and this can be translated into a standard list of items to include. Secondly simplicity of the method can be set by limiting the amount of parts of the yacht on which in formation has to be gathered. And finally the transparency of the method is enlarged since it will be known to everyone what is included in the YETI score. For the standardization a framework is created for the quantification of materials.

In order to create a standardized framework for the quantification of the materials, also referred to as the Life Cycle Inventory, first the requirements for the framework are set. Next different existing breakdown structures are compared and one is chosen as the base of the framework for the YETI. The breakdown structure is then expanded to include the information needed for the calculation of the environmental impact of a yacht for all three life phases.

4.3.1. Choosing a structure

To organize all the information about used materials and their weight it is necessary to choose a structure for the framework for the quantification of materials. As there are already different breakdown structures for ships and yachts available, these will be compared. The decision on which breakdown structure to use is based on two requirements as will be explained.

Requirements

The choice for the structure of the framework for the quantification of the materials has two main requirement. The first one comes from the requirement that the YETI can be used to compare yachts of different designers and build at different yards. Furthermore, it is important that the structure helps to organize material and weight information.

1. It should be plausible that different yards and designers can easily relate information to the framework
2. It should contain or allow for expansion to create a link with used materials and different life phases

Breakdown structure

Using a breakdown structure as the base for the framework of the quantification of the materials complies with the requirement to allow for expansion to create a link between a part of the yacht and a material. As explained in paragraphs 3.1 and 4.2.3, only the materials used on a yacht will be taken into account. In order to find a structure different product breakdown structures are compared. There are three breakdown structures that are compared:

- Feadship breakdown structure
- UNAS breakdown structure [10]
- PCR for yachts [17]

First the breakdown structure used at Feadship represents a structure used in the industry. Second, the structure used for the "Uniforme Administratie voor de Scheepsbouw" (UNAS) is considered as it was once created and required as structure to allocate material cost for yards in The Netherlands. It seems that yards in The

Netherlands are still using it, Damen Shipyards uses an updated version [43]. The breakdown structure of the PCR for yachts, developed in Italy in 2015, is the third one considered as it represents an idea of how possible environmental assessments will be organized. The structure of UNAS is created for all types of vessels and the PCR is created specifically for yachts. This mainly translates in a more detailed breakdown of the interior system.

The breakdown structure of UNAS and the PCR, though being developed in different countries and about 45 years apart, show significant similarities. The breakdown structures use almost the same demarcation between different items. An example of what is meant by levels is given in figure 4.2. Meaning that there are large similarities in first level items and the second level items per first level group are similar as well. This makes it very plausible that when yards use either one of the breakdown structures they can easily relate information to the other structure. They both have the same amount of levels, namely three: level 0, 1 and 2, this is an advantage as it would be relatively simple to expand the structure with an extra level to create a link to the quantification of materials.
Comparing the structures of UNAS and the PCR to the one used at Feadship more differences can be found. The breakdown structure of UNAS and the PCR show great similarities on all levels, however the breakdown structure of Feadship is different when looking at the first level. Yet on the second level the same systems/products are found. This indicates that it would be relatively easy to transform the structure used at Feadship into one of the other two and vise versa. Meaning that for all breakdown structures it is plausible that yards can easily relate information to one of the breakdown structures.

For the framework of the YETI, the choice is made to use the breakdown structure of the PCR. This is done because it is not linked to a company and more updated than the structure of UNAS. Additionally it has the advantage of being the structure that is used in Yachting 4.0 (see paragraph 4.4.3), a software program that is under development for the YETI.
The information for the case study was available in the Feadship breakdown structure and thus the items had to be linked to the structure of the PCR. This required a regrouping of some of the second level items and since the names of the items on the second level were similar this required no further actions. The other requirement was that it should be possible to expand the structure, this will be discussed in the following paragraphs.

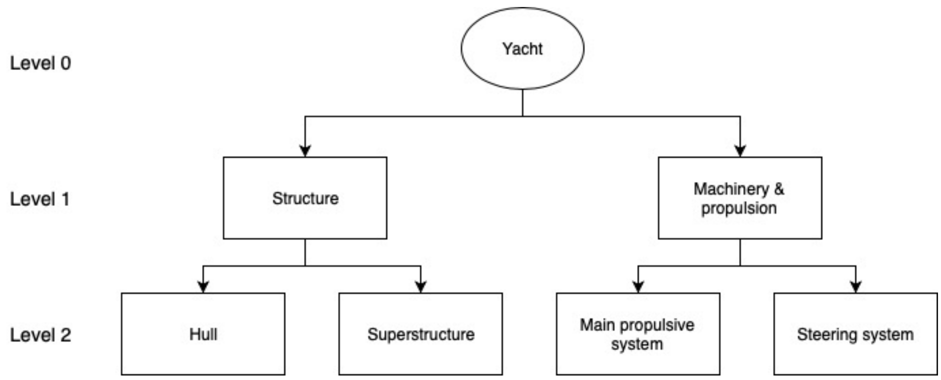


Figure 4.2: Levels used in the PCR for yachts

4.3.2. Framework for building

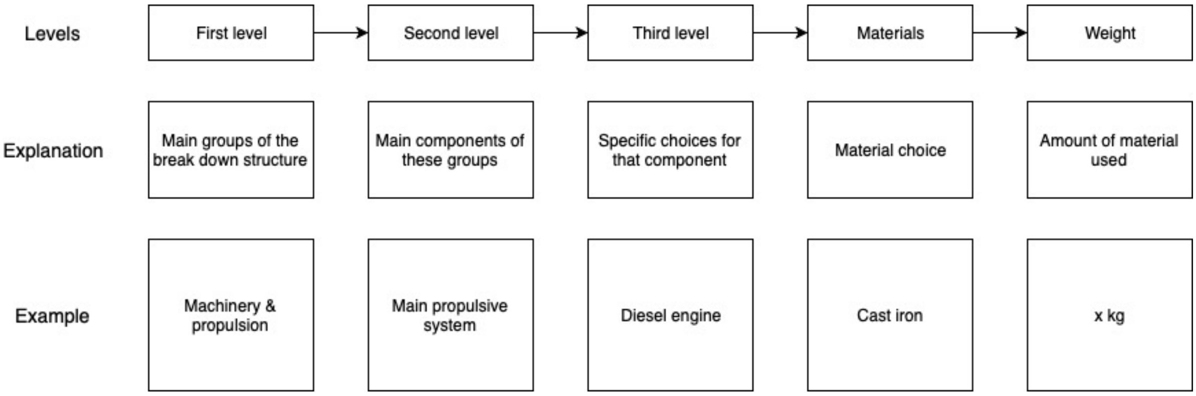
As a first step of the LCI an overview of the breakdown structure is made where the different levels, systems/products and materials are numbered. This numbering is done according to the system of numbering used at UNAS. However, an extra zero is added in front to create a difference between production(0), maintenance(1) and end of life(2). First the structure will be explained based on the production phase. This results the numbering of the first level as shown in the first two columns of table 4.5. The second level that belongs to the first level groups is also displayed but without numbering. Examples of the numbering of the second (and third levels) are shown in 4.3b, 4.4 and 4.5.

	First level	Second level
0100	Structure	Hull, superstructure, masts, main machinery foundation
0200	Machinery & propulsion	Main propulsive system, steering system, manoeuvring system, stabilizing system
0300	Ship systems	Fuel oil system, bilge system, HVAC system, black and grey water system, fresh water system, fire extinguishing system, sea water system, hydraulic system
0400	Ship systems	Airvent system, exhaust gas system, pool water system, refrigeration system, compressed air system, waste oil & sludge system, ballast water system, lubricating system, scrupper system
0500	Electrical system & electronics	Energy generation system, energy storage system, cables and wires
0600	Deck machinery & equipment	Anchor system, cranes, doors and hatches
0700	Paint & insulation	Exterior painting system, fairing system, insulation, cathodic protection, anti-fouling
0800	Internal joinery & outfitting	
0900	External outfitting	

Table 4.5: Structure for the LCI framework with the use of levels

So far only numbers have been added to the existing PCR breakdown structure but to link the second level to materials an extra third level is required. For example, on the second level there is the main propulsive system for which there are multiple options such as diesel, diesel electric, full electric and for the future there might be propulsive systems based on other fuels. These different options all have a different use of material and therefore it is important to add a third level in which these options are made visible and can be linked to the right materials. An overview of the levels and an example which is based on the machinery and propulsion is given in figure 4.3a. Besides, figure 4.3b shows what this looks like in the input sheet of the framework.

The other expansion made is a link of the third level to materials. The goal of the YETI is to keep calculations simple and therefore it was chosen to use Fast Track LCA which has an advantage that no full inventory has to be made of every possible material used. It requires the use of the main materials used in a system. Therefore, the choice has been made to limit the options for the material choices of the third level items. For the structure of the yacht this is relatively simple, in general there are only three materials used: steel, aluminium and composite. Although a steel hull contains some high strength steel it is dominated by the use of regular steel(97%) and thus the assumption can be made that it will exist of only regular steel. On the other hand, when looking at the main engine, it is a complex system made out of many different materials. Using Fast Track LCA allows to make rough assumptions about these complex systems. This is in line with the goal of the YETI to compare, since the same material will be selected for every diesel engine. The goal is not to compare the diesel engines but to compare the yacht that uses the type of propulsion for which a diesel engine is needed.



(a) Overview of the LCI structure

YETI inventroy framework							0 - Build	
1		2		3		Material	Weight	Material details
200	Machinery & Propulsion							
		210	Main propulsive system	211	Main engine(s)	Cast iron	x	

(b) Framework example for the diesel engine

Figure 4.3: Example of the diesel engine

Limiting the options for the selection of materials has another advantage. Using standard materials for systems gives more transparency as everyone knows which materials are used to model a system. In the example of figure 4.3a the material linked to the diesel engine is cast iron. This information was obtained for the case study. Figure 4.3b shows how this is implemented in the framework, this is the framework that the user of the YETI score should fill in. In the orange box in the weight column the user needs to fill in the weight of the main engine. In a yacht there are also systems the are composed of more materials where just assuming one dominant material is not sufficient. It is possible to create combinations of materials for third level items. An example of this is given in figure 4.4 for the fuel oil system on board. The weight that has been filled in in the orange boxes (the input data boxes) is chosen arbitrary to illustrate how the framework works and bears no resemblance to reality.
Predefining multiple materials for one third level item exists of four steps:

1. Write combination in the *Material* choice column
2. Write the different materials of which the item exists in the boxes below
3. Write the relative distribution of materials in the *Material details* column
4. Fill in the total weight of the item in the weight column
   The framework will calculate the weight per material

The weight per material will be used for the further calculations for maintenance and the end of life scenario.

YETI inventroy framework							0 - Build	
1		2		3		Material	weight	Material details
300	Ship systems							
	350	310	Fuel oil system	311	Pumps	Cast iron	100,00	
				312	Piping	Combination	200,00	
						steel unalloyed	100,00	50%
						galvanized steel unalloy	100,00	50%
				313	Appendages	steel unalloyed	50,00	

Figure 4.4: Example of multiple predefined materials for one item

4.3.3. Framework for maintenance

Another extension of the breakdown structure is needed to take the maintenance and end of life scenario, as defined in paragraphs 3.2 and 3.3, into account. For the maintenance schedule the same breakdown structure can be used as displayed in table 4.5 but replacing the 0 with a 1 for the first level. However for this research the only maintenance taken into account is the painting and the protection of the exterior of the yacht. For this reason only the Paint & insulation of the first level is considered and indicated with 1700 as shown in table 4.6. Figure 4.5 shows how this is adopted in the framework, the weight given in the figure are not representative. Because the maintenance activities take place every 2.5 or 5 years it is easy to calculate how often they come to pass in the yachts life time, either 7 or three times. For this reason the weight information about the material use for the maintenance does not have to be provided but can be calculated by multiplying the weight information on paint and hull protection with the amount maintenance takes place.

	First level	**Second level**
1700	Paint & insulation	Exterior painting system, cathodic protection, anti-fouling

Table 4.6: First and second levels for maintenance

YETI inventroy framework							**0 - Build**		**1 - Maintenance**	
1		**2**		**3**		**Material**	**weight**	**Material details**	**Times**	**Summed weight**
700	**Painting and Insulation**									
		710	Exterior painting system	**711**	Underwater hull	paint	1.000,00		7	7.000,00
				712	Hull above WL	paint	1.000,00		3	3.000,00
				713	Hull inside shell	paint	2.000,00		-	

Figure 4.5: Framework including the

4.3.4. Framework for end of life

The inventory for the end of life scenario is based on the assumption that every yacht will get a major refit after 20 years as explained in 3.3. This major refit will mark the end of life moment of the yacht and the start of the life cycle of a new yacht. In this scenario the structure and main machinery will be kept, this means that the 100 and 200 groups will be kept as well as the pumps from the 300 and 400 groups. The piping and appendages of these groups will have to be replaced. This splits the materials in two groups, materials that will be reused and materials that will be scrapped. Besides the option to reuse materials they can also be recycled. Both are implemented in the life cycle and how they can be taken into account in the framework for the inventory is discussed in this paragraph.

Reuse of materials

The structure and main machinery of the yacht will remain and be part of the new yacht while the rest of the yacht will be stripped at its end of life moment. There are multiple options to take this into account in the inventory of materials. The difference is mostly in the division of the impact of the used materials over the different yachts that use the structure and main machinery. These options will be discussed before choosing one to be implemented in the inventory.

- Zero impact for refitted yacht
  The first option is to allocate the entire impact to the first yacht that uses the materials that will be reused. This would mean that the impact of a refitted yacht is much lower then when the owner wants a completely new yacht. Therefore, this option would stimulate the refit sector and give a disadvantage to new build yachts. Implementation of this option into the inventory would mean that for refitted yachts the weight of the materials used for the structure and the main machinery can be set at 0 kilogram [51].

- Allocation based on the value of the hull
  Allocation based on the value of the structure and its main machinery is an option as well. Figure 3.5 showed how the value of the whole yacht decreases over time and that after 20 years it stabilizes at a price per gross tonnage that is about one third of the new build price. However, no information is available on the part of the second hand price that is for the hull of the yacht.

- Equal distribution
  Another possibility is to divide the impact equally over the different yachts that will use the structure and the main machinery. The lifetime of the hull and main machinery is approximated at 40 years. This means that two yachts will use the same structure and dividing the impact means that each yacht gets 50% of the total impact. Implementation of the equal distribution of the impact to the inventory would mean taking only 50% of the weight of the hull and main machinery into account.
  There is one slight disadvantage of the equal distribution as the impact will be the same for a new build yacht and a second hand yacht. A second hand yacht does have a smaller impact on the environment as it does require less extraction of materials from nature.

Chosen reuse scenario

The choice has been made to use the equal distribution in the framework for the use of materials. However, this is not the optimal solution because it does not favor refitted yachts which are more sustainable in terms of material use. For this reason some balance between having an equal distribution and allocating the larger part of the impact to the "first" yacht would be better. There are two main reasons why this is not implemented. First, non of the previous researches used such a scenario and therefore it is unknown if the reuse scenario has a significant influence. Secondly, as part of the YETI discussion no debate has been taken place on this topic. Equal distribution of the reuse scenario contributes to the underestimation of the environmental impact that is also created by the system boundaries. As part of the sensitivity study the influence of the reuse scenario can be investigated. Resulting in the possibility to make a better informed decision on the allocation of the impact due to the reuse of materials.

Recycling of materials
Some of the materials used on yachts can be recycled. To know for which materials it is important to obtain the recycling rates and implement these in the framework, the assessments discussed in paragraph 1.2.4 are used. In paragraph 3.3 the system boundaries for the end of life scenario are given. As for all processes in all life phases the recycling process itself is not taken into account, only how much material can be recycled. The reduction of material, meaning that because of recycling a part of the material can be reused, is accounted for. This means that the energy required for the recycling of the material is not. Vogtlander [69] describes two ways to take into account the recycling of materials: The first one takes the effect of recycling into account at the end of life stage and the second option deals with it at the start of the life cycle. The second option means that the material that is recycled is subtracted from the amount of primary material needed. The second option has an advantage because of the long life time of yachts and especially its steel parts.

When subtracting the recycled material from the amount of primary material that is needed, an unrealistic situation is created for steels [69]. This is because of the growth in the production of steel over the past decades in combination with long life time of steels. Over the past decade the steel industry has grown significantly, the total production from 20 years ago is equal to roughly 40% of the current production of steel. If all of the material from products that were produced 20 years ago is recycled only 40% of the steel products that are produced today can be made out of recycled material. It is thus important to take into account the current market ratio between scrapped material and primary material available(40/60%). According to Vogtlander this should be taken into account and this is easier to do with his second option of including the effect of recycling by subtracting the effect at the beginning of the life cycle. This is adopted in the model for the use of steel as it is one of the main materials used in the construction of a yacht. However, the growth of the steel production has been significant in the past but since the YETI will be adopted for future use it is important to consider the future growth of the industry. For the coming two decades it is predicted that the growth will be about 15% [20].

This information should be combined with information on the recycling process of metals. For this study the system boundaries exclude in the impact from energy used. Meaning, the YETI will only account for the recycling rates and not the recycling process. Steel is a material with good recycling properties and Broadbent [14] estimates that that the recovery rate for steel is 85%. Combining this with the information on the market growth the used recycling rate becomes 69%. However, excluding recycling processes contributes significantly to the underestimation of the environmental impact of yacht production. In the same study Broadbent shows the difference in impact, only taking into account CO_2, when energy required for the melting of the scrapped steel is taken into account. The CO_2 emissions of a kilogram of new steel are 1.756 kilogram and for a kilogram of recycled steel this is 1.405 kilogram. Meaning that when the recycling process is taken into account the reduction, with respect to CO_2 emissions is only 20%. On the other hand, the other impact categories are not taken into account in this research. The impact of recycling of steel with respect to resource depletion is 100% as steel can completely be recycled. As information on the recycling processes with respect to different impact categories is missing, it is not possible to implement this in the framework. For the YETI this means that the used recycling rate are probably a overestimation as the impact of the recycling process is not accounted for. As a result, the YETI score for the entire life cycle is likely an underestimation.

For the other metals less the recycling rates are based on literature [14, 67] and checked with the recycling rates used for the in-house research of the conceptual yacht [31]. The recycling rates are taken as the amount of material that is in the product at the end of life moment divided by the amount of material that is left after the recycling process [67]. Again, the recycling process itself is excluded from the assessment. For example the heat required for melting gold to give it a new shape is neglected. As shown in table 4.7 most of the recycling rates are given as a range, since the impact from the processes is not included the used percentage is chosen as the average.

Metal	Recycling rate range [%]	Recycling rate chosen [%]
Chromium	87 - 93	90
Iron	52 - 90	70
Nickel	57 - 63	60
Aluminium	42 - 70	65 [31]
Copper	43 - 53	50 [34]
Zinc	19 - 52	35
Lead	52 - 68	60
Gold	90 - 100	90
Lithium	<1	0
Steel, unalloyed	77,8 [14]	77,8 [14]
Cast iron	-	70
Steel, low alloyed	-	60
Stainless steel	33 [41]	33

Table 4.7: Recycling rates of metals
Based on "Recycling rates of metals" [67] unless otherwise indicated

Implementation of reuse and recycling in the framework
Both reuse and recycling of materials cause a reduction of the total impact of the materials used in the yacht. Vogtlander argues to implement the influence of recycling as a reduction of the amount of material that is used. This is implemented in the framework for both recycling and reuse. The reduction of the recycling of a material is defined by the recycling rate times the weight of that material used in the building and maintenance life phase. After the recycling weight is subtracted the reuse scenario can be calculated. 50% of the weight that is left over after recycling is subtracted from the weight after recycling. What is left is the amount of weight for the material that is used as input for the calculation of the environmental impact. This process is shown in figure 4.6 where the material weight box on the right represents the input in the calculation set up(paragraph 4.4.3). The recycling rates and reuse percentage are fixed for every YETI assessment but as said for the reuse another percentage than 50% might be favorable. Therefore the framework is constructed in such a way that this can be easily adjusted when necessary and set as the new standard for the YETI reuse scenario.

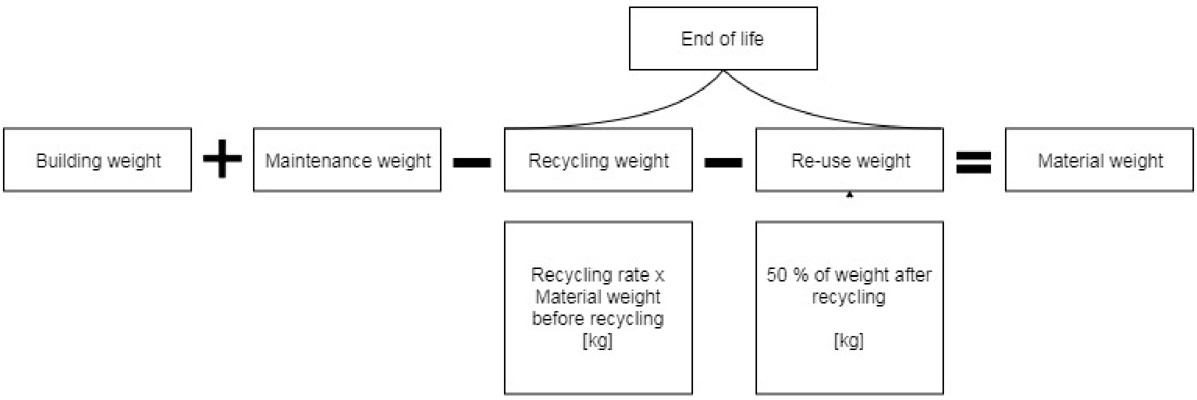


Figure 4.6: Implementation of the reuse and recycling scenario in the framework

4.4. Step 4: Perform the assessment

To perform the assessment there are three more choices which have to be made. First there is a need for information that links the materials to their impact on the environment. The ecoinvent database is used for this which will be further explained in this section. There are different ways to calculate the environmental impact and these methods are included in dedicated LCA software programs. The second choice is about the Life Cycle Inventory Assessment(LCIA) method which is linked to the choice of impact categories, and the last choice is that of the use of a LCA software.

4.4.1. Ecoinvent database

In order to perform the assessment there is the need for a way to link the materials that are used to the impact on the environment. There are different databases that contain information about the impact caused by the use of an unit (kg, m^3 etc) of resources. By combining information of different materials and energy it is possible to calculate the environmental impact of a product with these databases.
An accredited database, which was also used in the research of TNO into yacht X, is the ecoinvent database. This database covers over 10.000 processes and is the result of a joint effort of Swiss institutions. Experts from these institutions are responsible for the gathering of data and another group is responsible for quality control of the database. The use of this database was highly recommended by both Lucinda Kootstra[1] and by Vienna Eleuteri[2].

Ecoinvent applied for a yacht

The framework is created by using the information from the case of yacht A. For the assessment a link had to made between the third level of the framework and the used material. To do the assessment this material had to be found in the ecoinvent database. Though this database contains over 10.000 processes the yachting industry uses very specific materials. The result is that not all materials that are used in the yacht could be found in the ecoinvent data. This had to be solved by either one of three ways:

- **Choosing a similar material**
- **Simplifying the material**
- **Creating the material**

Materials for which it was needed to use one of these solutions are: teak, epoxy paint, galvanized steel and cunifer. How this was done is explained in appendix D. However, it is highly uncertain as to what extent the solutions for the materials that were not in the ecoinvent database are correct. As an example, teak is one of the materials that the yachting industry wants to replace because of it is made out of rare teak trees. In the current model the impact from teak is lower then that of the use of plywood. The same holds for the epoxy paint that was created in the eco invent database. Paint was one of the materials that was expected to have a high environmental impact but the maintenance, only consisting of painting, in only 0.66% of the total impact(see results 5.2) showing that paint has no significant impact at all in the calculation of this research.

These uncertainties about materials used for yachts that are not included in the ecoinvent database show a need for an extension of this database for yachts. This is necessary because the impact is now underestimated and also improvements with respect to the use of paint and teak can not be assessed. Further research should be conducted to create environmental information about these materials.

The factor of time in the ecoinvent database

In paragraph 1.2.4 the effect of different sources for the environmental data was already described to be significant. For that reason, the ecoinvent database is selected as the environmental database for the YETI. But even when using the same database the factor of time can influence the comparison between yachts. Over the years more and more information on substances that are harmful to the environment is gained. The fact that the world wide knowledge changes over times influences the environmental data. For example the IPCC (International Panel on Climate Change) updates the values of the global warming potential every few years [61, 62]. An update of such values get incorporated in the newest version of the ecoinvent database resulting

[1] sustainability consultant at TNO
[2] Initiator and vice chair of Water Revolution foundation. She has coordinated several international projects in sustainable development, human health and the environment [6]

in differences in the impact of the same material over time. This effect is hard to overcome. A solution could be to store the information from the framework for the life cycle inventory. Only this is the kind of information that yacht designers and yards do not want to make public as it is information on the weight of the yachts. An option could be to store this data with an independent third party. If it is possible to store this data the assessments could be redone to check the influence of the updated ecoinvent database.

4.4.2. Assessment method

Within every life cycle assessment model there is a choice between different methods for the calculation of the environmental impact. These methods are called Life Cycle Inventory Assessment (LCIA) methods. When a material is selected from a database such as the ecoinvent database and the weight of that material is known the LCIA method relates this to the environmental impact. The framework created in paragraph 4.3 functions as the inventory that is assessed with the LCIA method. This process is shown in figure 4.7. Since the Fast track LCA method is used for the model only single indicator LCIA methods are considered.

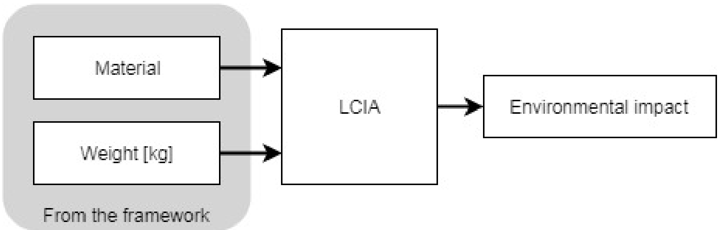


Figure 4.7: Life Cycle Inventory Assessment

Eco cost

Eco cost is an prevention based assessment method [69]. "Eco cost are the cost of the environmental burden of a product on the basis of prevention of that burden" [69] Meaning that the eco costs are additional cost that should be made to reduce the environmental impact to a level that the world can sustain. Per impact category there is a level at which the emissions are in balance with the earth's natural systems. This level is called the no-effect-level. The eco costs are the costs to take impact reducing measures up to that level. For example the no-effect-level for greenhouse gases is the level that the emissions and the natural absorption of the earth are in equilibrium, with a maximum rise in temperature of 2 degrees. In the prevention curve the relation between the cost and the level of prevention is shown. An example of such curve is given in figure 4.8 where the no-effect-level is displayed as well. The eco cost are the prevention cost at the no-effect-level.
An advantage of using eco cost to express the environmental impact of a product is that it is expressed in a standardized value (€) which is easily understood [69], and is based on the situation in the EU.The calculation of the eco cost is the same as for other indicators up to midpoint levels. "Schaduw prijzen" is the Dutch version of eco cost and based on a local prevention curve that gives cost of the prevention level required by the Dutch government [69].

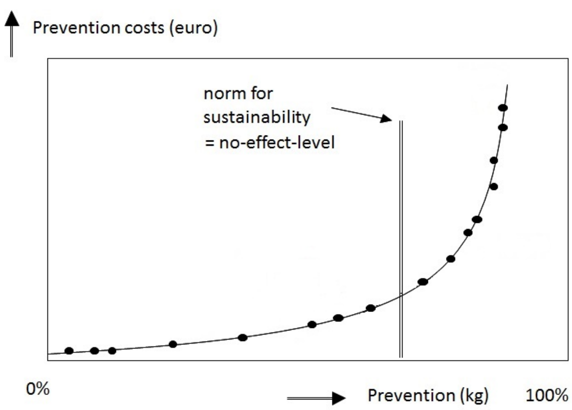


Figure 4.8: Prevention curve [4]

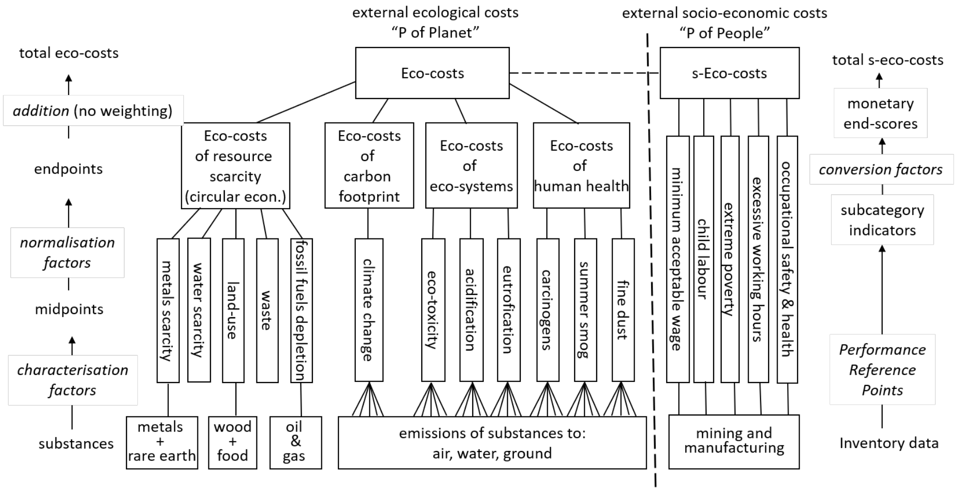


Figure 4.9: The eco cost calculation structure [69]

Recipe

Main difference with eco cost is that Recipe is a damage based assessment method. Eco cost calculates the cost(based on known technologies) that are required to keep the impact below predefined levels. Recipe relates the impact on impact categories(midpoints) to three end point categories: damage to human health, environmental health and resource depletion(Endpoints). Hereafter normalization and weighting is necessary to sum up the impacts of these three different endpoints. This means that the three categories have to ranked to each other.

For the newest version of Recipe(2016) no normalization and weighting factors are released [53] and thus the version from 2008 has to be used. These factors are needed to add up the impact on the damage categories to a single indicator. As Recipe is a further development of Eco Indicator 99 method it also uses eco points to express the impact.

Comparison on weighting method

As explained in paragraph 2.3.2 the single indicator LCIA methods have larger uncertainties. Between Recipe and eco cost these uncertainties come from different issues. For Recipe, and also eco indicator 99 in the past, these uncertainties come from the normalization and weighting step. Normalization is done based on the impact of an average European person and weighting is done based on social science. Meaning that where midpoint and endpoint indicators are calculated based on scientific models the step to go from endpoints to a single indicator requires less certain assumptions made on social science. The difference between the eco cost method and Recipe is the use of a different form of normalization and no use of weighting to get to the single indicator. Normalization in eco cost is done by calculating the prevention cost of a region and weighting is not necessary at all because cost can be added without the need for value choices. How this translates to the calculation structure of the eco cost is given in figure 4.9. Here normalization is applied to go from midpoints to eco cost for a specific end point. From there the only step is to add these cost to get the total eco cost.

Both methods have uncertainties but it is not possible to say which are more significant. But the uncertainties from the eco cost, coming from the price of a prevention method, seem to be more influenced over time. This because current technology changes rapidly and that would alter the outcome of the YETI assessment. Over time the YETI results would than be harder to compare.

Comparison on impact categories

In order to choose a LCIA method it is checked that both methods take into account the most important impact categories for yacht production. An overview of different impact categories is given in appendix E. To get some idea of the relevance of these impact categories it is checked if they are included in the PCRs. This is shown in table 4.8 where the X means that the impact category is included in the LCIA of that PCR. Most interesting is to see that the PCR for yachts does not include the impact category for the depletion of resources.

This means that it is not taken into account that resources get scarce, however all the emissions linked to the further manufacturing of these resources into materials or products is taken into account through the other impact categories.

1	2	3	4	Impact category
X	X	X	X	Climate change / Global warming potential - The emissions of greenhouse gases
X	X	X	X	Acidification - The emissions of acidifying gases
X	X	X	X	Photochemical Ozone formation - emissions of gases that contribute to the creation of ground level ozone
X			X	Stratospheric Ozone Depletion -
X	X	X	X	Eutrophication - Emissions of nitrogen's and phosphorus substances causing oxygen depletion
		X	X	Abiotic resource use - use of fossil fuels and minerals
		X		Water use -
X				Noise

Table 4.8: Impact categories included in different Product Category Rules
1. PCR for Yachts [17] 2. PCR for Airplanes [13] 3. PCR framework for transport [3] 4. PCR for buildings [19]

The PCR for yachts asks for additional or explicit mention of the emissions covered by Marpol Annex VI, NO_x, SO_x, VOC emissions and ozone depleting substances. These emissions are listed by Camprara [15] and contribute to Acidification, Photo-oxidant formation, Eutrophication and ozone depletion [59]. This explains why stratospheric ozone depletion is included in the PCR for yachts.
When looking further then the PCRs common sense and the results of earlier research can be used to indicate other relevant impact categories. Chatzinikolaou and Ventikos [18] concluded that the emissions of CO_2, CO, NO_x and SO_2 have the largest impact. These emissions are linked to the impact category climate change. For the use of materials the impact categories for the depletion of biotic and abiotic resources should be considered. Combining all these impact categories results in the list:

- Climate change
- Acidification
- Ozone depletion(Photochemical & Stratosheric)
- Eutrophication
- Biotic resources
- Abiotic resources
- Photo oxidant formation

Except for ozone depletion all these impact categories are included in both the eco cost and Recipe method. Ozone depletion is missing in the eco cost method, which is a disadvantage. How significant this disadvantage can be checked with the case study.

Chosen method
The choice is made to use the Recipe method for three reasons. First is the inclusion of all the impact categories that are considered to be of interest for the yachting industry. Second is the method is more stable over time. And finally eco cost has the disadvantage of adding an extra price to the yacht.
However, up to mid point level the methods are very similar. Therefore it would be good to require both the results of the single indicator but also the midpoints indicator values for each assessment. This would ensure that if the LCIA methods change in the future a comparison on midpoint level is still possible.

4.4.3. LCA software

LCA software is used because it provides the calculation methods necessary to translate the information from the ecoinvent database to the impact. The chosen software for the calculations is Simapro, which is one of the leading software tools for LCAs [54]. The available license at the TU Delft provides not only the required access to the software but also access the the ecoinvent database. As another option the open source LCA software Open LCA was considered. However, this software does not provide a significant advantage over

Simapro and doesn't contain a link with environmental databases. These databases have to be manually uploaded when using OpenLCA.
Over the past years an environmental researcher, Vianna Eleuteri, has started to develop a LCA software dedicated to the yachting industry: Yachting 4.0 [21]. This software is also linked to the YETI project. It tries to create an environmental database specified for the yachting industry with a calculation method that takes into account the relevant impact categories for the industry. The environmental database will also be based on the ecoinvent database but the expansion can help to solve the problems with the materials that were not found in ecoinvent. The reason that Yachting 4.0 was not used for this research is that it is still under development. The design of the framework for the LCI has been created in such a way that it can also be used with the Yachting 4.0 software.

The framework that is constructed for the quantification of materials is created in Simapro as well. Doing this makes it easier to put the information from the framework (the materials and their weights) to the processes in Simapro.

4.5. Step 5: Interpret the results

Due to the use of the single score and the simplified assessment of the materials that are used(the framework for the LCI) there are a few things to keep in mind when interpreting the end results.
First the outcome of the assessment can not be regarded as the real environmental impact of a yacht. Due to the simplifications the outcome is more an estimation of the impact. The distribution of the impact over different parts of the yacht can be analysed. It will become clear which systems are likely to have a large impact. The outcome should be used only for comparison to other yachts that have been assessed according to the same methodology. This is what the framework is designed for and can be done based on the end result being lower(better) of higher(worse) then the result of another yacht.

One of the requirements of the YETI is not fully met, manipulation of the method is still possible. During all meeting that were held to gather information on the materials used the question came up: Is it possible to check the information? Very often the answer was no because not all the materials are weighted before they are installed on the yacht. And after installation it is not possible to check individual weights of items but only the total weight of the yacht checked when it has been launched. Meaning that both when the yacht is in the design phase as when the construction is finished the input of the YETI can be manipulated by the designer or yard. This can be done in either one of two ways. First it is possible to say that less of a material is used. Or secondly by saying a different material is used. Setting predefined materials for some of the third level items in the LCI framework was tried as a solution to prevent manipulation as much as possible. Validation of the method with more yachts than the case study from Feadship should indicate if enough items have gotten a predefined material or if it is necessary to predefine more materials in the framework.

4.6. Conclusions on the model

In this chapter a model is created that is based on the Fast Track LCA methodology and the production life cycle created in chapter 3. The different steps of Fast Track LCA are further standardized to make comparison of the outcome of the model possible. An overview of the created model is given in figure 4.10.

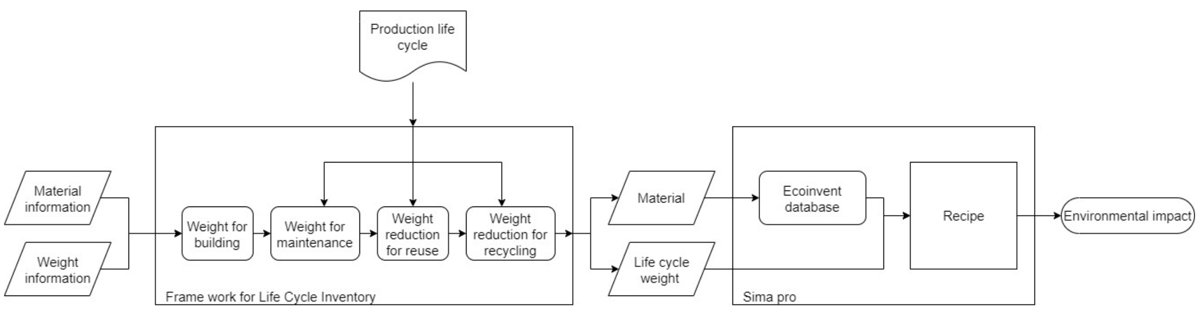


Figure 4.10: Created model of Fast Track LCA

On the left side the model starts with the information of the used materials in the building phase of the yacht and the weight of these materials. This is input for the standardized framework for the quantification of the materials. This framework uses this input data and the standard life cycle to calculate the weight for maintenance and the amount of material that is reused and recycled. The result for every material is the total weight that should be accounted for during the life cycle: the life cycle weight. The combination of the materials and its life cycle weight is input for Simapro. In Simapro the materials used on the yacht can be linked to environmental information using the ecoinvent database. After this step all information is documented in Simapro and the next step is selecting Recipe as the LCIA and the environmental impact is calculated by Simapro.

The model that is created should comply with the five requirements of the YETI as given in paragraph 1.1.1. First, this means that the model should be transparent. In paragraph 1.1 three question were defined to assess if the used information is transparent. The first two, how van information be obtained and what is done with this information, can be answered for input data necessary for the model. The information can be obtained by weight calculations and because of the standardized LCI framework it is known how the information is used. However, the third question whether the input data is verifiable can not be answered positively. It is not possible to check the input data and this is one of the biggest flaws of the model. Meaning that the designed model itself is transparent but how the input data is obtained is not. This leads to one other requirement that is not met. Manipulation of the assessment should not be possible, but as input data can not be verified it is possible. Manipulation of the model itself is not possible.
The rest of the requirements of the YETI are met. The model is designed to be understandable for users having basic knowledge of yachts and access to the weight calculation of the yacht to be assessed. Effort is minimized by the creation of the standardized framework for the quantification of materials (also referred to as the Life Cycle Inventory). Next to this, the model is designed to compare the outcome of different yachts by using Fast Track LCA and a single indicator method.

5 Case study & results

The previous chapters contain information on relevant topics in order to eventually come to the framework for the Life Cycle Inventory as described in paragraph 4.3. To test the framework for the LCI, it will be applied to a yacht that has been built by Feadship in the recent years. This yacht will be called yacht A. The assessment serves two goals, the first goal is to check if the LCI is easy to use with the available data. The second goal is to check if comparison based on the LCI with its current level of detail is possible. This will be done with a sensitivity analysis were the effect of possible design choices will be investigated. The effect of design choices has to be visible in order to compare different yacht designs.

5.1. Application of the LCI framework on the case

To check if it is possible to apply the model created in chapter 4, a case study was performed. For each first level group an explanation will be given on how information was gathered and if any assumptions were made. An important source of information on the yacht has been the weight calculations of De Voogt. These calculations are done in the breakdown structure that is used by De Voogt and therefore had to be adjusted to fit in the LCI structure for the YETI.

Structure

Information on the material for the structure is available in the general information on the yacht. The structure consists of the hull, superstructure, mast and main machinery foundations. The assumption is made that the second level items hull and superstructure consist of one of the three materials: steel, aluminum or composite together with glass. The masts and main machinery foundations are modelled with only one material. It was possible to get all the data from the weight calculations.

Machinery & propulsion

For the Machinery & propulsion assumptions about the materials for the main (diesel) engines, gearbox, propeller shaft, rudder, bow thruster, stern thruster and stabilizers were made together with one of the naval architects from De Voogt. The main engine and bow and stern thrusters are modelled as cast iron and other components as unalloyed steel. For the propeller, consisting of nickel aluminium bronze material, the percentages are set at 5, 9.5 and 4,75 and the rest is copper [58].

Ship systems

Precise and detailed information on the materials used for the different ship systems was limited available. For that reason information was gathered from the sheet containing material and weight information of the design of the ship systems. This information sheet was constructed before the design of the systems of yacht A was finished. This information was used nonetheless to calculate the percentage of a material used for the piping, pumps and appendages. However the total weight of the systems in this sheet was slightly lower than the weight found in the weight calculation and therefore the results are scaled. For this case study this information is used, but for future use of the YETI the advise would be to validate the percentages for the materials used with other vessels. As said in paragraph 4.3 this validated information on ship systems can be used to predefine materials. This way the user of the YETI doesn't have to do these calculations themselves and limiting the choice in used material gives more transparency. It is known to anyone which materials and in which combination they are used. If for the design other materials are used the burden of proof is only for designs using different materials.

One other difficulty was that all the information of air related systems was put together under HVAC in the sheet that was used to calculate the percentage of materials used of the systems. For this reason it seems like most of the air systems are not installed on the yacht but actually they are all summed up in the HVAC item. The same goes for the fire fighting and fire extinguishing system, there was no separation between the two so there is only the fire fighting system.
Information on the hydraulic system was only available on the miscellaneous part of this system.

Electrical system & equipment
The electrical system & equipment group consists out of three parts: Energy generation, Energy Storage and Cables and wires. Information was easily found in the weight calculations done by De Voogt. In Consultation with RH Marine [57] the cables for the electric system are modelled as fully copper.

Deck machinery and equipment
For deck machinery and equipment all information was found in the weight calculations performed by De Voogt.

Paint and insulation
Detailed information was gathered on the different layers of the paint system on the yacht. The paint and fairing used is all epoxy based but every layer is a different epoxy paint. Information on epoxy paints is not available in the eco invent database and there was only enough information available to create one paint (explained in appendix D), therefore all the paint and fairing is modelled the same.

All the insulation of the yacht is put in one item on the weight calculation sheet. Getting more detailed information on the different materials used for the insulation on the yacht was not possible. For this reason all the insulation is modelled as glasswool.

Interior
The interior for the yacht is designed by an external company and therefore there are no details about the weights or the used materials. An idea was to collect information on the material ordered by the yard to get an indication of the amount of material used. Unfortunately this information was not complete, especially for the luxury interior where one would expect rare materials that can have a large environmental impact. The interior of the conceptual yacht compared in paragraph 1.2.4 was based on the interior of other Feadship yachts. The goal of this design was not to optimize the interior but was more focused on new propulsive systems. The distribution of materials of that concept yacht is scaled to the total weight of the interior of the yacht for this case study. For this reason it was not possible to link the materials to the third level created for the LCI whereby the model is slightly adjusted.

Exterior
For exterior all information was found in the weight calculations done by De Voogt.

5.1.1. Conclusion about the application of the framework for the LCI

Making use of the case study it is possible to check if the framework for the LCI complies with the requirements of the YETI as given in paragraph 1.1.1. According to these requirements the framework should be understandable and use with minimal effort. The information from the weight calculation sheet of De Voogt could be related to the framework's third level items with minimal effort. Though using the framework complies with the requirements for the YETI, significant difficulties were encountered with respect to data availability. Especially data availability on the materials that are used was lacking for this research. Especially for the interior and the ship systems a more detailed investigation of the materials per third level items requires significantly more effort. For the ship systems the solution is a deviation of each system into pumps, piping and appendages and using a predefined distribution of materials. The use of predefined materials is also adopted in the framework for the LCI. For the interior the solution of using a distribution based on other yachts is used in the case study. However this solution allows for little variation between yachts and is therefore not preferred for the comparison of yachts and will not be adopted in the framework. Solving this would require a new way of keeping track of used materials at shipyards. This is also seen in the implementation of the IHM(Inventory of Hazardous Materials) were the wish is formed to get more detailed information from suppliers about the materials used in their products. Keeping track of used materials, not only for the IHM but in general and for all suppliers would significantly improve the availability of input data for the LCI framework.

5.2. Results of base case

In this section the results of the case study with yacht A are given. First the results for the total life cycle are given and compared to previous research for verification. Then the results are analysed in more detail in order to indicate important impact categories and parts of the vessel with a large impact.

The results of the case study are given in table 5.1. The total impact over the entire life cycle of yacht A is 216,025.7 eco points.

Life stage	Yacht A
Total	216,026
Building	790,723
Maintenance	1,430
Recycling	-550,799
Re-use	-25,339

Table 5.1: Results for yacht A in eco points

To check if this outcome is reasonable the result can not be compared with the assessments of yachts X and Y because over time the data has changed significantly. In order to make this comparison possible, the information on the building phase of yacht X is used to redo that assessment. It is not possible to do this in the framework for the LCI as created in this research because the information in the report from 2009 is given per material without a link to the items for which this material was used. The result for the building phase of yacht X with recipe 2008 and the current ecoinvent database version is 1042,608 eco points and the weight of the materials included in this assessment is [confidential] ton in total (97%of total weight). For yacht A this is 790,726 eco points and in this assessment [confidential] ton of material is assessed (90% of the total weight). Because of the difference in weight percentage that both assessments account, the eco points per ton are calculated for both yachts and shown in table 5.2. The eco points per kilogram for yacht A are only 5.8% lower than for yacht X.

	Yacht A	Yacht X*
Impact of building	790,726 Pt	1042,608 Pt
Weight percent that is included	97%	90%
Impact per ton	780 Pt	735 Pt

Table 5.2: Comparison between yacht A and X*
* assessed with Recipe2008

The results of the assessment are dominated by one material: Gold. To show this dominance the assessment has been done an extra time without the use of gold for the interior and these results are shown in figure 5.1. Gold is the material with the highest impact per kilogram but also the material that is most easy to recycle, which is expressed with a high recycling rate. Because of these significantly higher values for gold this causes

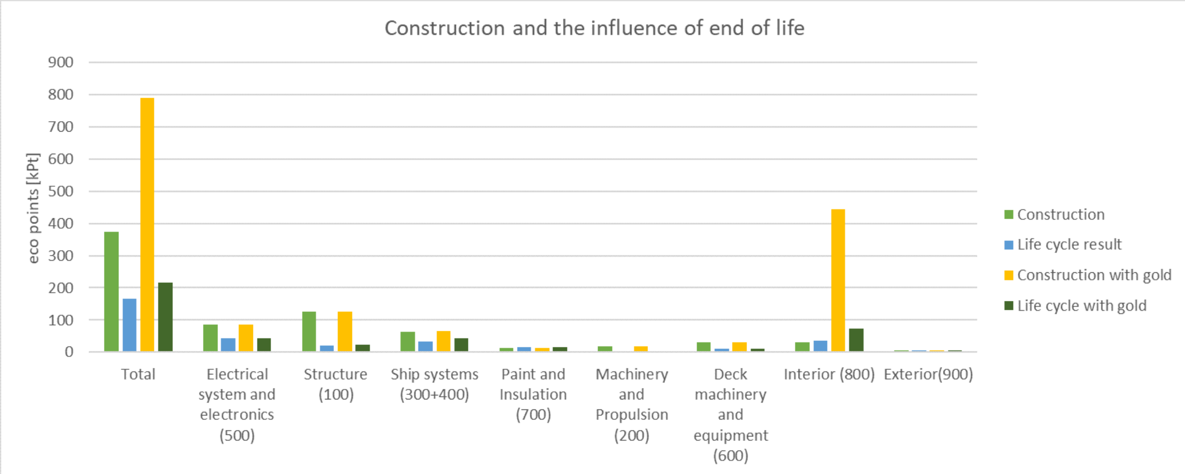


Figure 5.1: Results per life phase including the influence of gold

almost half of the total impact of the building and recycling phase. Although only 78 kilogram of gold is used the impact of gold for the building phase is 413,131 eco points. The effect is similar with the assessment of yacht X with EI99 where the influence of gold is 157,868 eco points. The difference is explained by the increase of eco points per kg of gold from 1579 with Eco Indicator 99 in 2009 (when yacht X was assessed) to 5297 eco points per kg with Recipe(2008) in 2019 for yacht A. The difference can be caused either by an update on the impact from gold in the ecoinvent database or by a different weighting in the impact assessment methods Eco Indicator 99 and Recipe(2008). The influence of the use of gold dominates the results, therefore some results will also be analysed without gold to get a better view of other differences. This domination of mainly the building and recycling phases results in a low significance for the total life cycle. This is displayed in figure 5.1 where the difference for the construction with or without gold is larger than the effect on the impact from the whole life cycle.

Figure 5.2: Influence of each life phase
Gold is left out of this graph

Influence of reuse and recycling

The influence of the different life phases can be seen more clearly in figure 5.2 where it is displayed per first level group. This graph shows three interesting things. First the re-use of materials is visible for the structure and the also for the main machinery and propulsion. However, in the end of life scenario the pumps of the ship systems are also re-used. The influence of the re-use of the pumps is not zero, but comes very close with just 270 eco points. This can be explained because the pumps are mostly modeled as cast iron which has a high recycling rate and the total weight of all pumps, even before recycling, is just 7827 kilo. To simplify the model further it would be interesting to take the pumps of the ship systems out of the re-use scenario. It is probable that this will not show in the result as it is now 0.125% of the total impact.
Furthermore, the total effect from the implementation of the re-use scenario is a 12 to 14% reduction of the total impact of the production life cycle depending on the inclusion of gold in the assessment. Most of the materials that will be re-used are materials with high recycling rates(metals). The high recycling rates lower the impact from these materials significantly and thus the impact of the re-used materials as well.

Figure 5.2 and table 5.1 show how significant the influence of recycling and reuse actually is. The total impact from production (791 kPt) gets lowered to 216 kPt over the whole life cycle, which only 27% of the impact from the building phase. These results are highly dominated by the effect of gold. Leaving gold out of the assessment the impact over the life cycle gets reduced by reuse and recycling to 46% of the impact from the building phase. The choices made in the model for recycling and reuse are thus very influential for the end result of the assessment. And, these choices lead to a lower score for the impact form yacht production. For comparison this is not very relevant but it gives a wrong estimation of the total impact from production. Reflecting on the choices for the recycling and reuse there are two things that are good to reconsider.

First, in the whole study the influence of energy is outside of the system boundary. However, the energy used for the basic material production is included in the information from the ecoinvent database. This means that for the steel used in the assessment the energy is taken into account. For recycling the energy required to transform scrapped steel into steel that can be used in the next product is excluded. Broadbent [14] gives the indication that the impact from recycling is significant, which means that the influence of recycling is overestimated, making the effect of excluding energy even bigger on the underestimation of the impact. Inclusion of the energy required for the recycling is possible as every yard uses dedicated recycling companies. Meaning, that if this information becomes available, including the impact from recycling of metals could be standardized and adopted in the framework and thus fulfill all YETI requirements.

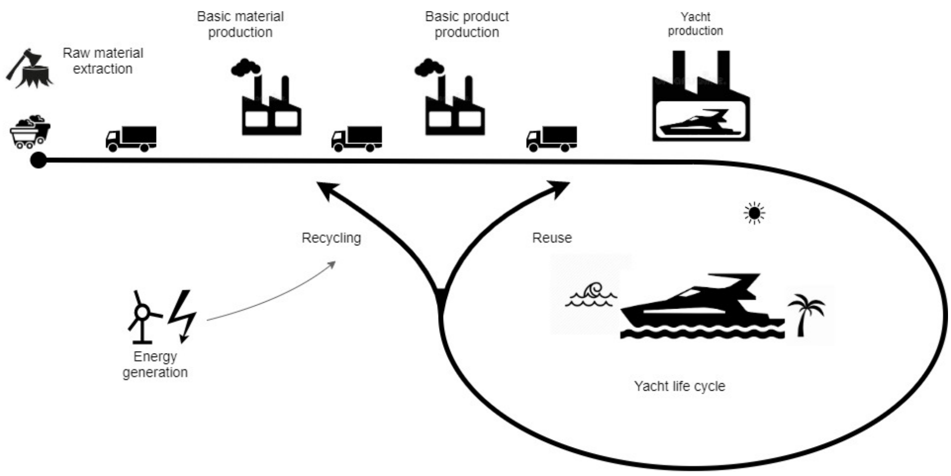


Figure 5.3: Simplified life cycle showing the difference between recycling and reuse

Second, the reuse scenario has a significant influence of the end result and changing the ratio of allocation between the first (new) build yacht and the second (refitted) yacht can make a difference. If the larger part of the impact from materials that are reused is allocated at the first yacht it will become clear from the YETI score that this is worse for the environment then buying a second hand yacht and doing a refit. The YETI would in this way help to stimulate the refit market instead of the new build market. As it is expected that non of the items that are reused needs large maintenance the second hand yacht really saves the production of these items. For this reason it would be reasonable to allocate all the impact from these materials to the first yacht. But, this is not entirely fair. The difference between reuse and recycling is that recycling requires energy. In other words recycling creates an extra impact were reuse does not. Figure 5.3 illustrates this difference by the different paths in the life cycle. Therefore, a better option than allocating the entire impact to the first yacht would be to allocate only the benefit of not having to recycle the material to the second yacht.

Analysis of the different groups

Besides the influence of reuse and recycling, figure 5.2 shows the first level groups that are most impacted by the production life cycle of yacht A. These are the electrical system & electronics, ship systems, interior and structure. Here the difference between a yacht and the tanker researched by Chatzinikolaou and Ventikos, as discussed in paragraph 1.2.1, becomes very clear. Where for shipping vessels the impact from the construction (the use of steel) is most significant, figure 5.2 shows that for yachts this is not the case. The impact is not dominated by the use of steel but divided more over the different groups.

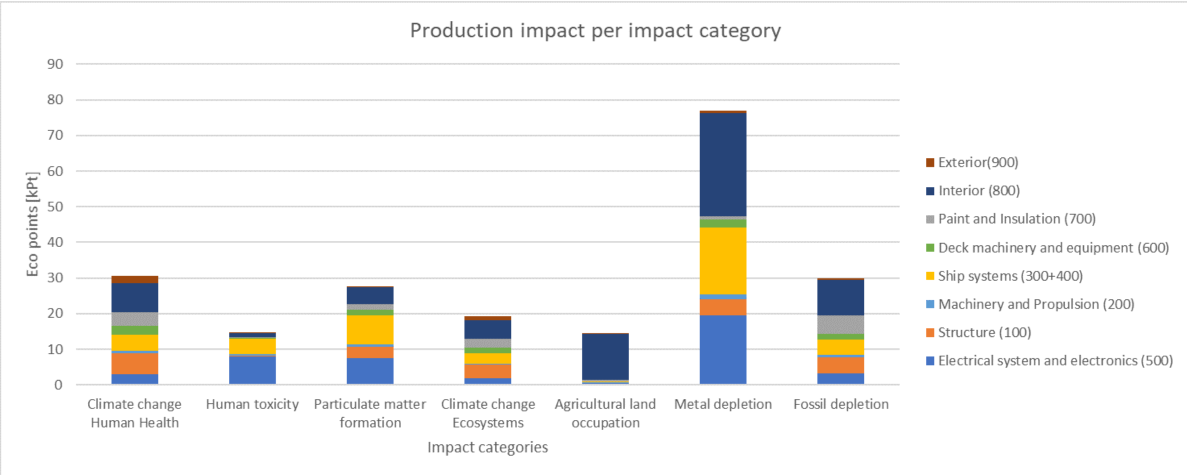


Figure 5.4: Impact on the different impact categories

Also interesting in figure 5.2 is the very small impact caused by the exterior. In both the assessments of yacht X and Y the exterior has a significant share in the total impact. In both assessments this was caused by the teak deck. This does not show in the results for the assessment of yacht A. Teak wood was not found in the ecoinvent database and other databases were used to create teak wood as explained in appendix D. However the selected teak wood from the database has an impact that is lower per m^3 then that of plywood. In both the other assessments teak wood has a larger impact and from literature it was expected that the impact from teak is significant [50]. For further use of the model it would be beneficial to do more research on the impact caused by teak wood.

Analysis of impact categories

With the results it is also possible an analysis can be done to see which impact categories are most affected by the production life cycle of yacht A. There are seven impact categories that were affected the most by the production life cycle of yacht A. The effect on these impact categories was at least 10 times larger then on the other categories included in the Recipe 2008 method. The effect on these impact categories is shown in figure 5.4 per first level group. In this graph the influence of Gold is again significant. The entire dark blue part of the impact category metal depletion is caused by gold. The large impact caused by the interior on agricultural land use comes from the other materials in the interior.

The largest impact is caused to metal depletion by the metals used in ship systems and the electrical system. In terms of weight these are not the heaviest groups but the more rare metals used for these systems have a significant influence on the total environmental impact. One could be surprised that fossil depletion

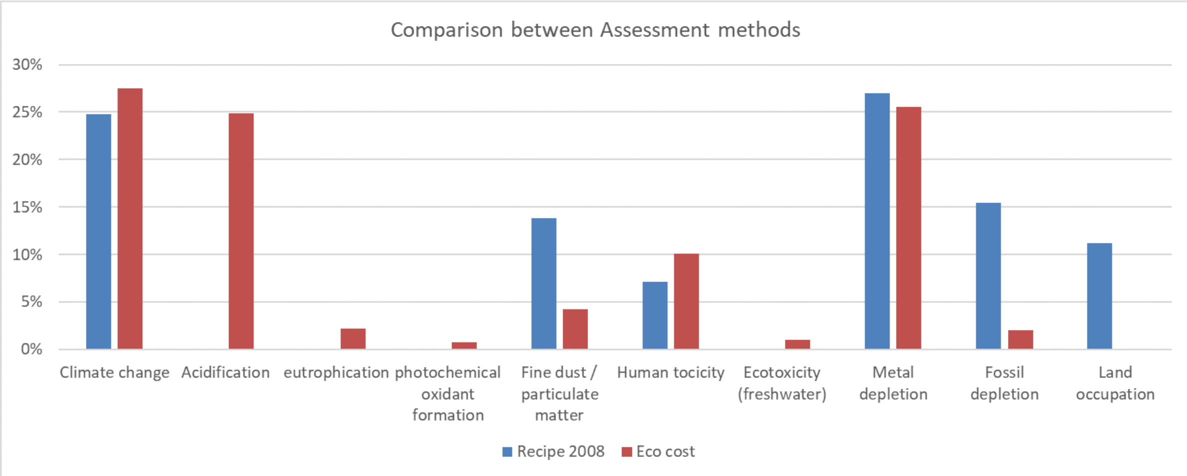


Figure 5.5: Comparison of effected impact categories when using the eco cost or Recipe method

is a impact category that is affected by yacht production in the same range of magnitude as the other impact categories. The fossil depletion is likely caused by the production processes of the basic materials, as information on these production process is included in the ecoinvent database.

The Recipe 2008 method was used because this single indicator method uses eco points. Eco points are preferred over the euro's used in the eco cost methodology but also because in the eco cost method ozone depletion was missing as an impact category. However, this was one of the impact categories that was least impacted by the production life cycle of yacht A. For this reason the same assessment of the impact over the whole life cycle was carried out with eco cost. Since the eco point can not be compared directly with the eco cost(euro's) only the distribution of the impact over the different impact categories can be compared. This is shown in figure 5.5. Interesting is the difference between the distribution of the impact over the impact categories using Recipe 2008 and the eco cost method. The impact on acidification is low when using Recipe 2008 and large when the eco cost method is used. The difference is due to different approach that both methods have. Which one is correct requires more knowledge of environmental science.

5.3. Sensitivity to design choices

The framework for the YETI has been created using assumptions on material use. For this reason it is important to check that the simplified version of the life cycle inventory has enough sensitivity to show a difference in the end result due to design choices. For this reason two design choices, the use of aluminium for the hull (1), because using aluminium requires less material, and second the application of batteries(2), because they save energy in the operational phase, are investigated. Besides that the influence of energy used at the yard is checked, as described in paragraph 3.1 it is complicated to create system boundaries when it comes to the use of energy and it was therefore excluded. However this also means that in the current model only the design is assessed and not the yard. To investigate the influence of the yard a case is created that includes energy used at the yard.

5.3.1. Aluminium hull

The hull of yachts is normally made from steel or aluminium, and some yards build in composite as well. Yacht A was originally made from steel but it is checked what the influence is of using aluminium. Using aluminium has as a big advantage that it is lighter than steel. In the operational use of the yacht a lighter yacht needs less power for the propulsion and will therefore use less fuel. A calculation has been performed to calculate what the weight would be of the hull of yacht A when made out of aluminium instead of steel. No effect to the propulsive system due to the lower amount of required power has been taken into account. Only the hull material and weight are adjusted.

Results

Using aluminium for the hull will decrease the weight of of the yacht. However, the impact of one kilogram of steel is about one third lower than the impact from one kilogram of aluminium. One kilogram of aluminium has an impact of 0.357 eco points and steel has 0.224 eco points per kilogram. Meaning that it is possible that though less material is used the impact will not be significantly lower.

		Life cycle [kPt]	Life cycle	Structure [kPt]	Structure w.r.t life cycle
With gold	Steel hull	216	100,0%	22	100,0%
	Aluminium hull	212	98,0%	18	81,2%
Without gold	Steel hull	174	100,0%	22	100,0%
	Aluminium hull	170	97,6%	18	81,2%

Table 5.3: Decrease of impact due to the use of an aluminium hull

The results of the assessment done with the aluminium hull are shown in table 5.3. As can be seen the result over the entire yacht and over the entire life cycle is very small. The results are split in the results when gold is used in the interior and when gold is not used in the interior because of the large impact of gold. In both cases the impact due to the use of aluminium instead of steel for the hull is relatively small, only a reduction of 2 and 2,4 percent on total impact. On the structure itself the reduction is 18.8% which is a significant reduction. This difference is better visible in figure 5.6 where the impact is given per group. Aluminium thus has a lower impact when used for the hull material.

Figure 5.6 shows the impact divided over the different groups. This result is shown to check that only the impact of the structure has changed and the rest of the yacht remains the same. Showing that the model works as it is supposed to.

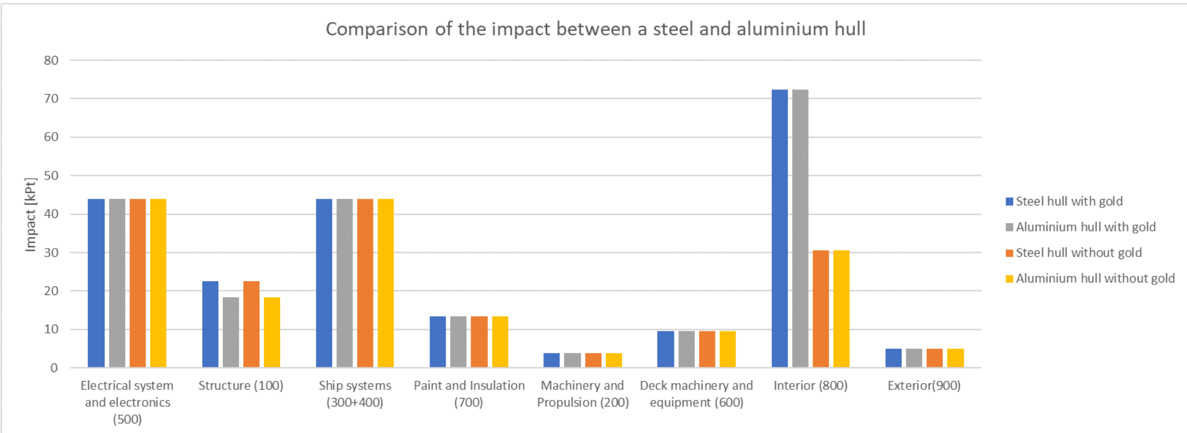


Figure 5.6: Results of the assessment with the aluminium hull

5.3.2. Use of batteries

Batteries can be used for different purposes on board yachts. Two cases have been explored for the use on yacht A, (1) for the use of peak shaving and (2) to go one night without the use of generators for the energy. A configuration for diesel electric propulsion is given in appendix C.

Batteries for peak shaving

Installing batteries for peak shaving has an advantage in the operational use of a yacht. Because of the extra power the diesel engine can run at a more constant power at a rpm for which the engines is efficient. The fluctuations in required power can be delivered by the energy stored in the batteries. When the ship is sailing the energy from the batteries is extracted when power demand is higher, and saved in the batteries again when the power demand is lower the the output of the diesel engines. For this reason the peak shaving batteries are power batteries, meaning that they are designed to have high charge and discharge rates(C-rates). Information for the capacity of the batteries calculated at De Voogt and the "Corvus Orca Energy" [9] is used to calculate the mass of the batteries required. Batteries are now sold with an life expectancy of 5 years [57], meaning that during the life time the batteries will have to be replaced 3 times. Because the batteries will not be used daily both the scenario with an life expectancy of 5, 10 and 20 years is modelled.

Results for the use of batteries for peak shaving

The results for the application of batteries used for peak shaving are given in table 5.4 together with the results from the base case for yacht A. The extra impact for placing the batteries is 4% and also visible in figure 5.7. This means that the use of energy does influence the result of the assessment of a yacht.
The increase in impact is already 4% when the maintenance of the batteries is not yet taken into account. Table 5.4 and figure 5.7 show the influence of the life time of the batteries as well. If the life time of the batteries is truly equal to 5 years and they will have to be replaced 3 times during the yachts life time the impact increases with 16%. The 16% increase just because of the addition of batteries is quite extensive, meaning that the amount of batteries seems to become a dominant factor.

A check is done to see if the use of the batteries changes the impact categories that are most effected. This is not the case and therefore figure 5.8 shows the same seven impact categories as for the base case.

	Life cycle [kPt]	Electrical system & Electronics [kPt]	Life cycle	Electrical system & Electronics
Base case	216	44	100%	100%
No maintenance	225	53	104%	120%
1 x replaced	234	62	108%	140%
3x replaced	251	79	116%	180%

Table 5.4: Increased impact due to the use of batteries for peak shaving

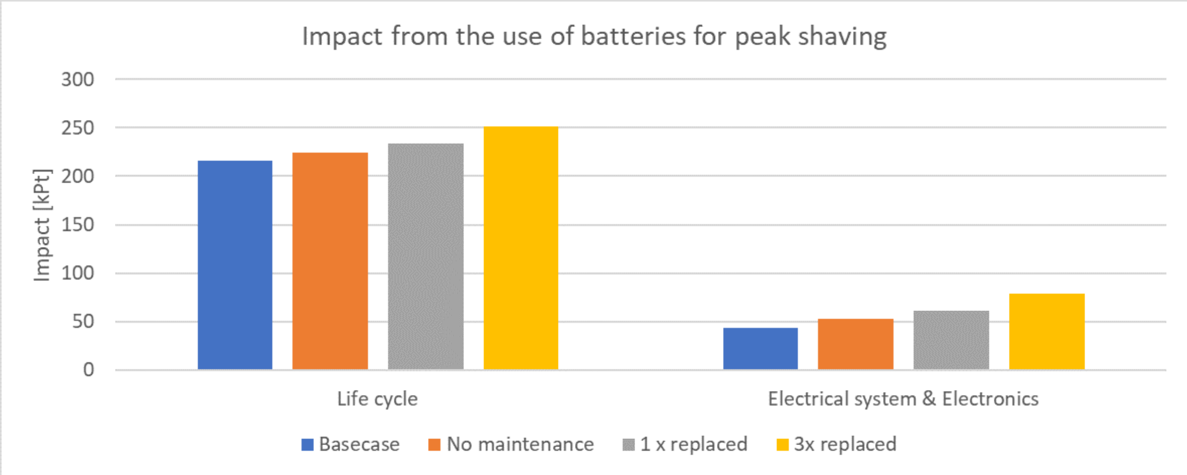


Figure 5.7: The growth of the impact in eco points caused by the use of batteries for peak shaving

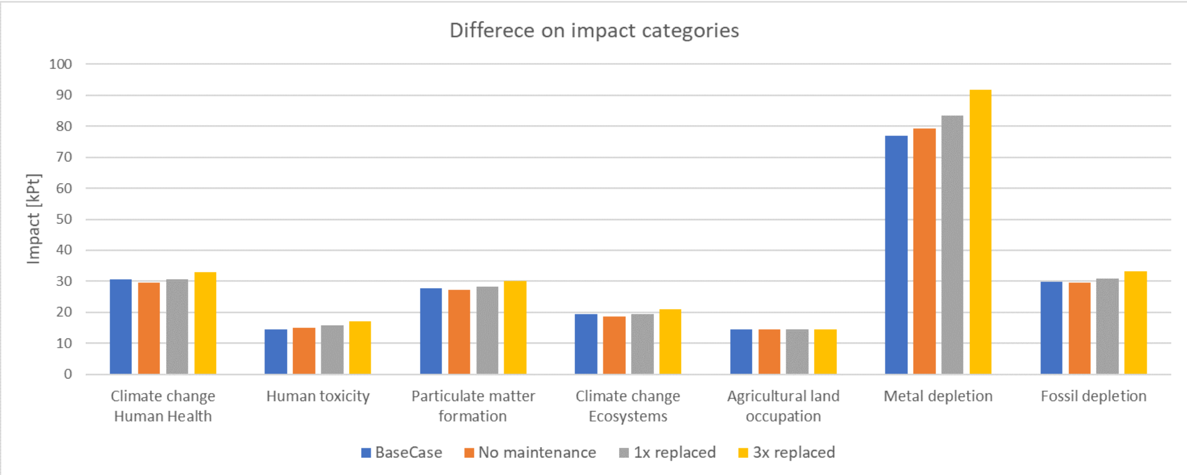


Figure 5.8: Impact of the use of batteries on the largest impact categories

Batteries for hotel load

A realistic design wish is to be able to go a whole night without the use of the generators to provide the yacht of energy. A night is taken as 10 hours during which the hotel load is half of what it is during the day. The energy that is required has to be stored for a long time and no high charge or discharge rates are necessary. The information to translate the required power to the amount of batteries that have to be placed on board is based on the specifications of the "Corvus Blue Whale" [1]. Due to the lower amount of charge cycles that the hotel load batteries will undergo, compared to the peak shaving batteries, the life time is estimated at 10 year.

Results

The results show a significant increase in the impact when the batteries are installed for hotel load. With the life time of 10 years, the batteries have to be replaced on, the total impact increases with 17%. Meaning that the impact from the batteries starts to dominate the total impact of the yacht. If the data is extrapolated to the energy required for the hotel load of a day the impact increases to 47%. Batteries are installed on yachts more often in order to decrease the impact during the operational use of the yacht. If the trend for the use of energy will increase over the coming years there is a chance that the impact from the production life cycle is completely dominated by the amount of batteries installed. Leaving the question whether it is necessary to put time an effort in gathering information on all the other materials used for the yacht when the result is dominated by the batteries.

	Life cycle [kPt]	Electrical system & Electronics [kPt]	Life cycle	Electrical system & Electronics
Base case	216	44	100.0%	100%
No maintenance	234	62	108.5%	142%
1 x replaced	253	81	117.1%	184%

Table 5.5: Increased impact due to the use of batteries

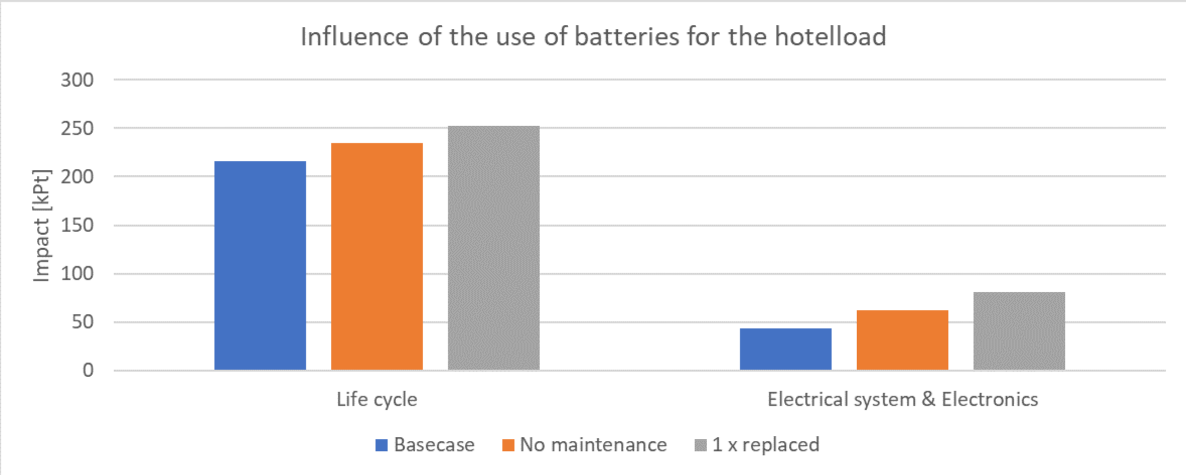


Figure 5.9: Influence on the impact over the life cycle when using batteries for the hotel load of one night

5.4. Effect of excluding energy

As discussed in section 3.1 it was not possible to find a system boundary that allows for the inclusion of energy used in the building processes and comparison. Therefore, this is excluded in the current framework. However, the exclusion of the required energy and the processes means that only the design of the yacht is assessed and not the yard that builds the yacht. Including energy (and yard processes) gives the builder of the yacht an influence on the total environmental impact of the yacht as well. Another effect is that it is likely that the impact from yacht production is underestimated when excluding energy. Unknown is the size of this underestimation. In this sensitivity check an investigation is done to gain more knowledge about the effect of this system boundary.

Two different types of used energy are distinguished, the used energy for the construction of the hull and the used energy for the assembly of the yacht. This distinction is made because of subcontracting as explained in paragraph 3.1. Data for both the energy use of construction and assembly was measured at the yards. The energy required for assembly of the yacht and construction of the hull is calculated based on the energy demand of the yards and split over the amount of docks (production places) that the yard has.

Nowadays their are different ways available to lower the energy demand, one of those is producing your own energy. The assembly yard has given an estimation of the energy that they could produce by placing solar panels on the roof. With this estimation five different cases are created for the profit of solar cells in terms of a reduction in energy demand.

Results

The results of the inclusion of energy for the construction of the hull and the Assembly of the yacht are given in figure 5.10. In other words the figure shows the current system boundaries for the assessment of yacht production underestimate the environmental impact by 40%. This is a serious part of the impact that will not be shown in the YETI results as long as the system boundaries exclude the use of energy.

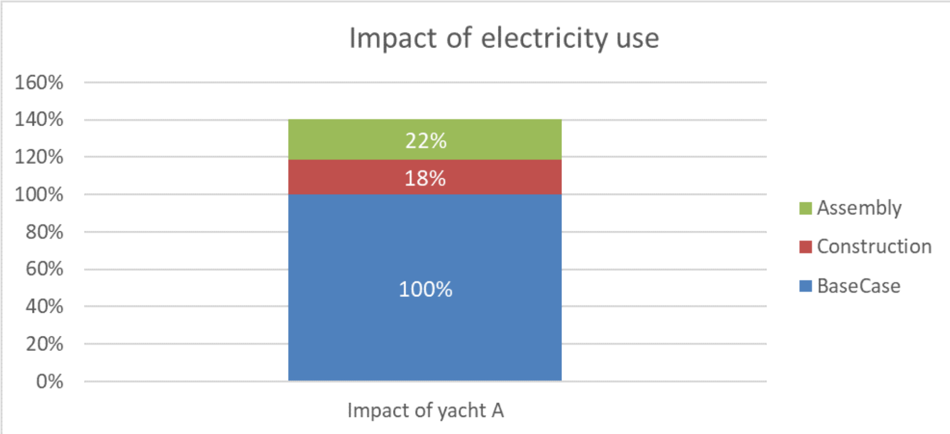


Figure 5.10: Influence of energy and solar cells on the total environmental impact of the yacht

One of the measure the yard can take in order to lower the impact from energy, is placing solar panels. Based on a real case of one of the yards to place solar panels, five case are created with a different amount of energy that is generated by solar panels. The results of these five care are shown in table 5.6 and figure 5.11. Though the energy used at the assembly yard is slightly larger, both yards are in the same range.

Scenario	Materials		Construction		Assembly		Total
	[kPt]	[%]	[kPt]	[%]	[kPt]	[%]	[%]
BaseCase	214.60	71%	0	0%	0	0%	71%
No solar energy	214.60	71%	39	13%	46.89	16%	100%
5% solar energy	214.60	71%	39	13%	44.55	15%	99%
10% solar energy	214.60	71%	39	13%	42.20	14%	98%
15% solar energy	214.60	71%	39	13%	39.86	13%	98%
20% solar energy	214.60	71%	39	13%	37.52	12%	97%
25% solar energy	214.60	71%	39	13%	35.17	12%	96%

Table 5.6: Influence of taking into account energy and use of solar cells

The influence of placing solar panels for the generation of energy might seem small, as it is a few percent. But, the scenario's with the solar cells show that if 10% of the energy can be excited from solar cells the reduction in impact(2%) is in the same range as using aluminium as hull material, having a 2% reduction in impact as well.

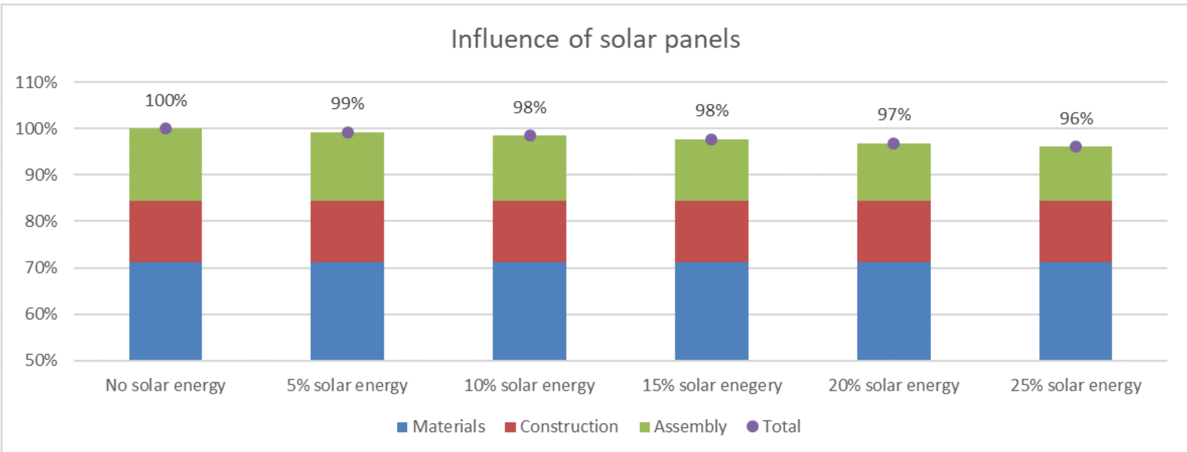


Figure 5.11: The influence of solar panels for the generation of energy

6

Conclusions and recommendations

This chapter gives the conclusions and recommendations on this research about the creation of a model to compare the environmental impact from yacht production. The chapter starts with the conclusion on the sub- and main research questions and finishes with the recommendations.

6.1. Conclusions

As was described in chapter 1, the aim of this research was to create a model that allows for the comparison of the environmental impact from the production of different yachts. The model composed in this research is to be used as part of the YETI, the Yacht Environmental Transparency Index. Because of the specific requirements of this index, non of the currently available models could be used.

First a methodology for the assessment had to be chosen in order to answer the question: **what is the best way to apply LCA for the calculation of environmental impact from yacht production?** Taking the specific requirement for standardization and comparison of the YETI into account, Fast Track LCA is the best suitable methodology. This method allows for the use of a single indicator assessment method, creating results that can be compared without in depth environmental knowledge. The other advantage is the more simplified version of the life Cycle Inventory; the quantification of materials. Standardizing this step leads to, not only a standardized method, but also more transparency, understandability and it minimizes the effort required for the calculation.

As the goal of this research is to compare the environmental impact from a life cycle perspective, the life cycle is standardized in this research. Before the life of a yacht begins the yacht is constructed, the building phase is the first life phase. When the yacht is delivered it will have a life time of 20 years. In these 20 years it will undergo significant maintenance 7 times. After 20 years the yacht will get a major refit which indicates the end of its life time. The structure and main machinery will go on with the next yacht and the rest will be stripped and recycled if possible. This provides the answer on **what the life cycle of a yacht is from a production perspective?** However, the aim of the YETI to compare yachts influences this life cycle significantly. The only part of this life cycle that can be compared are the materials that are used on board the yacht. Due to the large difference in the level of sub contraction at different yards, the used energy, transport, waste and the yard processes could not be included in the YETI assessment. Comparison is still possible on this life cycle but the outcome is an underestimation of the true impact from yacht production.

Both the Fast Track LCA methodology and composed life cycle are used to create a model for the assessment of yacht production. To create transparency and minimize the possibility of manipulation of this model, the sub question: **how information on the yacht and its production process can be measured and made transparent?** was composed. The best way to gather data and make it transparent is by doing this based on a standard framework for the life cycle inventory. Such a framework is created in this research based on the Fast Track LCA methodology. This framework is designed in such a way that it can be used based on the weight calculation of a yacht and that systems for which materials are hard to define are predefined. The framework was tested during a case study for which it was possible to relate yacht information to the framework with minimal effort. The limited availability of data of materials used on yachts does influence the link of the framework to the ecoinvent database.

To check the model a case study was performed in which the model was validated. The case study provided a base for a sensitivity check in order to check if **the results of the LCA are influenced by design choices and boundary setting?** The sensitivity to design choices was tested by three cases, an aluminium hull, batteries for peak shaving and batteries for the reduction of the hotel load. All design choices were visible in the results. Remarkable was the large increase in the impact of production when using batteries. This indicates it is likely that the impact from production will increase in the future due to innovations for the reduction of the impact from operational use.
The influence of boundary setting was investigated by checking how significant the exclusion of energy used for the production is. This system boundary contributes significantly to the underestimation of the total environmental impact from yacht production. If the energy for the construction of the hull and the assembly of the yacht would be taken into account the total impact increases by 40%. It was not possible to investigate the significance of the energy required for recycling, but it is probable that including this will make the underestimation even bigger.

6.1.1. Conclusions with respect to the main research question

The main research question that has been answered in this research is:
How can the environmental impact of yacht production be compared from a life cycle perspective?
The comparison of different yachts can be done based on the model for the assessment of yacht production created in this research. The model shows enough sensitivity and complies with the five requirements set for the YETI. It is designed for comparison, transparent, simple to use, standardized and the model itself can not be manipulated. However, the model is highly sensitive to the input data. The problem with this sensitivity is that it is not possible to validate the input data. A solution for the validation of the input data should be found.
Though the model that is created in this research is suitable for comparison it still has flaws. The main ones being the lack of environmental information on the materials used (such as paint and teak wood) and the missing information of an assessment of a yacht with a full Life Cycle Inventory. For this reason these items are listed in the next paragraph with the recommendations.

6.2. Recommendations

In this section the recommendation for future work are given:

- By choosing Fast Track LCA the LCI phase is highly simplified. This means that more detailed information on the materials embedded in systems is lost. The composed model for the assessment of the environmental impact from yacht production only works if more information is gained about the precise composition of systems and product on board. For this reason it is important that future research is performed that focuses on getting more environmental information with more detailed Life Cycle Inventory studies. This would help to get better predefined materials coupled to this level items of the framework

- Future research is necessary to create an environmental database or complement the ecoinvent database to a point were it contains all relevant materials for yacht production. This would require detailed LCA studies into these specific materials.

- The framework for the LCI contains predefined materials for some of the third level items. These predefined materials are based on the case study done in this research but need further validation based on information from other yachts.

- In the case study difficulty was experienced to gather information on the material use in the ship system but as engineering of these systems takes place at De Voogt information could be obtained and scaled to be of use for the case. For the information on the interior this was not the case. In general it was experienced that designers and yard keep track of materials that are used in a limited capacity. Future research on how information of used materials can be gathered and stored is of interest not only for the YETI but for regulations such as the inventory of hazardous materials as well.

- The system boundaries for the model as created in this research exclude the impact from yard processes and used energy. However, the results of the sensitivity analysis show that the impact from the energy used for the construction and assembly of the yacht accounts for an increase in impact of 40%. Future research should focus on getting more understanding of the environmental impact from important yard processes. Secondly, more research is necessary to find a way to include the energy used during the building phases.
- Following on the previous recommendation research into the impact caused by the recycling processes is required. All yards use dedicated recycling companies for the recycling of materials. Therefore, it is possible to standardize the recycling rates of metals including information on the recycling processes.

Bibliography

[1] Corvus Blue Whale - Corvus Energy. URL https://corvusenergy.com/products/corvus-blue-whale/.

[2] *ILCD Hanbook: General guide for Life Cycle Assessment*. ISBN 9789279190926. doi: 10.2788/38479. URL http://lct.jrc.ec.europa.eu/.

[3] PCR Basic Module CPC 49 Transport equipment v3.

[4] Eco-costs - Wikipedia. URL https://en.wikipedia.org/wiki/Eco-costs#/media/File:Fig_2_Wiki_ecocosts_pollution_prevention_curve.gif.

[5] SuperYacht Times | Yachting News, Photos & Intelligence. URL https://www.superyachttimes.com/.

[6] Board - Water Revolution Foundation. URL https://waterrevolutionfoundation.org/board/.

[7] YETI Meeting 25th of March 2019, .

[8] YETI Meeting 5th of September 2019, .

[9] Corvus Orca Energy - Corvus Energy. URL https://corvusenergy.com/products/corvus-orca-energy/.

[10] *Uniforme administratie voor de scheepsbouwindustrie : richtlijnen voor de uniformering van de calculatie en de administratie in de Nederlandse scheepsbouwindustrie. LK - https://tudelft.on.worldcat.org/oclc/67983193*. Stichting Nederlandse Scheepsbouw Industrie, 's-Gravenhage SE - Verschillende pag. ; 31 cm., 1970.

[11] REGULATION (EU) No 1257/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 November 2013 on ship recycling and amending Regulation (EC) No 1013/2006 and Directive 2009/16/EC. *Official Journal of the European Union*, page 20, 2013. URL https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R1257&from=EN.

[12] Ship recycling, 2019. URL https://ec.europa.eu/environment/waste/ships/.

[13] Bombardier Aerospace. UN CPC 49623: Passenger commercial aeroplanes. Version 1.0. pages 1–29, 2015. URL http://environdec.com/en/PCR/Detail/pcr2015-02.

[14] Clare Broadbent. Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy. *International Journal of Life Cycle Assessment*, 21(11):1658–1665, 2016. ISSN 16147502. doi: 10.1007/s11367-016-1081-1. URL http://dx.doi.org/10.1007/s11367-016-1081-1.

[15] Leo Campara, Nermin Hasanspahić, and Srdjan Vujicic. Overview of MARPOL ANNEX VI regulations for prevention of air pollution from marine diesel engines. *SHS Web of Conferences*, 58:1004, 2018. doi: 10.1051/shsconf/20185801004. URL https://www.researchgate.net/publication/329383051_Overview_of_MARPOL_ANNEX_VI_regulations_for_prevention_of_air_pollution_from_marine_diesel_engines.

[16] A.C. Cardoso, G. Free, P. Nõges, Ø. Kaste, S. Poikane, and A. Lyche Solheim. Lake Management, Criteria. *Encyclopedia of Inland Waters*, pages 310–331, 1 2009. doi: 10.1016/B978-012370626-3.00244-1. URL https://www.sciencedirect.com/science/article/pii/B9780123706263002441.

[17] Product Category, Rules According, and T O Iso. Product category rules according to iso 14025 date 2015-01-22. pages 1–32, 2015.

[18] Stefanos D. Chatzinikolaou and Nikolaos P. Ventikos. Holistic framework for studying ship air emissions in a life cycle perspective. *Ocean Engineering*, 110:113–122, 2015. ISSN 00298018. doi: 10.1016/j.oceaneng.2015.05.042.

[19] Product Category Classification and U N Cpc. Valid until: 2022-01-24. pages 1–45, 2018.

[20] Hang Dr. Cho and Moon-Kee Dr. Kong. The Steel Industry over de Next Two Decades. Technical report.

[21] Vienna Eleuteri. Yachting 4.0.

[22] H Ellingsen, A M Fet, and S Aanondsen. Tool for Environmental Efficient Ship Design. Technical report, 2002. URL `http://www.iot.ntnu.no/users/fet/publi-forfatterskap/publikasjoner/ensus-ellingsen-fet-2002.pdf`.

[23] Feadship. Feadship internal document: Overview of rules in yachting. Technical report.

[24] Annik Magerholm Fet. Environmental reporting in marine transport based on LCA. *Journal of Marine Design and Operations*, (1):1476–1556, 2002.

[25] Annik Magerholm Fet, Dina Margrethe Aspen, and Harald Ellingsen. Systems engineering as a holistic approach to life cycledesigns. *Ocean Engineering*, 62:1–9, 2013. ISSN 00298018. doi: 10.1016/j.oceaneng.2013.01.003. URL `http://dx.doi.org/10.1016/j.oceaneng.2013.01.003`.

[26] GAUSS. Ship life cycle assessment and management. (October):55, 2011. URL `http://archive.northsearegion.eu/files/repository/20140303142113_D3.5.5_ship_life_cycle_management(ed).pdf`.

[27] M. Goedkoop and R. Spriensma. The eco-indicator 99: a damage oriented method for life cycle impact assessment - Methodology Report. Technical Report April, Ministerie van Volkshuisvesting, Ruimelijke Ordening en Milieubeheer, 2001.

[28] Jeroen B. Guinée. *Handbook on Life Cycle Assesment*. KLuwer Academic Publishers, 692. ISBN 0306480557.

[29] Zerrin GÜNKAYA, Levent KARACASULU, Gülperi EVLİYAOĞLU, and Mesut ÇİFTÇİ. Life Cycle Assessment of Marble Plate Production. *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, 22(2):521, 2018. ISSN 1308-6529. doi: 10.19113/sdufbed.74350.

[30] Sjoerd Harren. Feadship internal ducument for the graduation of Sjoer Harren; The assessment of an actual yacht. Technical report, 2009.

[31] M Head and S De Vos. Feadship internal document on the assessment of the conceptual yacht. Technical report, TNO, Utrecht, 2010.

[32] Type Iii. Nen-en-iso 14025. 2010, 2019.

[33] IMO. ANNEX 17 RESOLUTION MEPC.269(68) (adopted on 15 May 2015) 2015 GUIDELINES FOR THE DEVELOPMENT OF THE INVENTORY OF HAZARDOUS MATERIALS. 269(May):56, 2015. URL `https://edocs.imo.org/Final`.

[34] International Copper Association. Copper Recycling. 2017.

[35] International Maritime Organization. Recycling of ships - The development of the Hong Kong Convention. URL `http://www.imo.org/en/OurWork/Environment/ShipRecycling/Pages/Default.aspx`.

[36] International Maritime Organization. MEPC 60/WP.6 - Prevention of Air Pollution From Ships, 2010. URL `http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx`.

[37] International Maritime Organization. Third International Maritime Organization Green House Gas study. Technical report, London, 2015. URL `www.imo.org`.

[38] International Maritime Organization. Initial IMO strategy o nreduction of GHG emissions from ships, 2018.

[39] ISO. Nen-en-iso 14040. Technical report, Nederlands Normalisatie-instittut, Delft, 2006.

[40] Karl Jivén, Anders Sjöbris, Maria Nilsson, Joanne Ellis, Peter Trägårdh, and Malin Nordström. LCA-ship, Design tool for energy efficient ships - A Life Cycle Analysis Program for Ships. Technical report, 2004. URL `http://www.mariterm.se/wp-content/uploads/2016/08/Final-report-LCA-ship.pdf`.

[41] Jeremiah Johnson, B. K. Reck, T. Wang, and T. E. Graedel. The energy benefit of stainless steel recycling. *Energy Policy*, 36(1):181–192, 2008. ISSN 03014215. doi: 10.1016/j.enpol.2007.08.028.

[42] Michihiro KAMEYAMA, Katsuhide HIRAOKA, Akio SAKURAI, Takeshi NARUSE, and Hiroaki TAUCHI. Development of LCA software for ships and LCI Analysis based on actual shipbuilding and operation (Summaries of Papers Published by Staff of National Maritime Research Institute at Outside Organizations). *Science*, pages 0–3, 2005.

[43] S Lely. Report number: SDPO.18.042.m. Technical report, 2018.

[44] M E Letschert. Developing a Method for the Construction of the Yacht Environmental Transparency Index. 2019.

[45] Lloyd's Register. The Rules and Regulations for the Classification of Ships.

[46] MEPC. 2014 GUIDELINES ON THE METHOD OF CALCULATION OF THE ATTAINED ENERGY EFFICIENCY DESIGN INDEX (EEDI) FOR. Technical report, IMO, London, 2017. URL `https://edocs.imo.org/Final`.

[47] R. B. Mitson. Underwater noise radiated by research vessels. In *ICES mar. Sei. Symp*, pages 147–152, 1993.

[48] Nederlandse Normalisatie-instituut. Nen-en-iso 14044. Technical report, Nederlands Normalisatie-instittut, Delft, 2006.

[49] Openbare Vlaamse Afvalstoffenmaatschappij. Ecolizer 2.0. Technical report, 2011.

[50] Samuel T. Partey, Oliver B. Frith, Michael Y. Kwaku, and Daniel A. Sarfo. Comparative life cycle analysis of producing charcoal from bamboo, teak, and acacia species in Ghana. *International Journal of Life Cycle Assessment*, 22(5):758–766, 2017. ISSN 16147502. doi: 10.1007/s11367-016-1220-8.

[51] Leonardo Postacchini, Giovanni Mazzuto, Claudia Paciarotti, and Filippo E. Ciarapica. Reuse of honey jars for healthier bees: Developing a sustainable honey jars supply chain through the use of LCA. *Journal of Cleaner Production*, 177:573–588, 2018. ISSN 09596526. doi: 10.1016/j.jclepro.2017.12.240. URL `https://doi.org/10.1016/j.jclepro.2017.12.240`.

[52] Pré consultants. Introduction to LCA with SimaPro Colophon. Technical Report November, 2016.

[53] PRé consultants. SimaPro Database Manual Methods Library Title: SimaPro Database Manual Methods Library Written by: PRé, various authors. page 75, 2019. URL `http://creativecommons.org/licenses/`.

[54] PRé Consultants. SimaPro | The World's Leading LCA Software, 2019. URL `https://simapro.com/`.

[55] Prof.ir. S Hengst. *Scheepsbouw Deel 1*. Delft University Press, Delft, 1999. ISBN 90-407-1850-4.

[56] Pruyn, Hekkenberg, and Van Hooren. Determination of the Compensated Gross Tonnage factors for superyachts. *International Shipbuilding Progress*, 57(3-4):127–146, 2010. ISSN 0020868X. doi: 10.3233/ISP-2010-0066.

[57] Dirk Jan Reijenga. RH Marine, 2019.

[58] Ivan Richardson. Guide to Nickel Aluminium Bronze for Engineers. Technical report, Copper Development Association, 2016. URL https://www.copper.org/applications/marine/nickel_al_bronze/pub-222-nickel-al-bronze-guide-engineers.pdfhttps://www.nickelinstitute.org/~/media/Files/MediaCenter/News/20160205-Guide_to_Nickel_Aluminium_Bronze_for_Engineers.ashx?la=en.

[59] Ralph K. Rosenbaum, Michael Z. Hauschild, Anne Marie Boulay, Peter Fantke, Alexis Laurent, Montserrat Núñez, and Marisa Vieira. *Life cycle impact assessment*. Springer Dordrecht Heidelberg New York London, 2015. ISBN 9783319564753. doi: 10.1007/978-3-319-56475-3{_}10.

[60] M A Shama, G G Soares, Y Garbatov, and N Fonseca. Life cycle assessment of ships. In *Maritime Transportation and Exploitation of Ocean and Coastal Resources, Vols 1 and 2*, volume 2, pages 1751–1758, London, 2005. ISBN 0 415 39036 2. URL http://eng.staff.alexu.edu.eg/~mshama/LCASO-215.pdfhttps://www.scopus.com/inward/record.uri?eid=2-s2.0-60749115039&partnerID=40&md5=0ba9100863a644ef1dc9e73036e45ae2.

[61] S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). *IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom adn New York, USA, 2007. ISBN 9788578110796. doi: 10.1017/CBO9781107415324.004.

[62] T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013. ISBN 9781107661820. URL http://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf.

[63] Times Super Yacht. Data sheet Super Yacht Times. Technical report, 2019.

[64] T Tincelin, L. Mermier, Y. Pierson, E. Pelerin, and G. Jouanne. A Life Cycle Approach To Shipbuilding and Ship Operation. *Ship Design and Operation for environmental Sustainability*, page 7, 2010. URL https://www.stirlingdesign.fr/presses/conferences/stirling_design_paper_ssd.pdfhttps://stirlingdesign.fr/presses/conferences/stirling_design_paper_ssd.pdf.

[65] Thibaut Tincelin. SSD « Sustainable Ship Design » A LIFE CYCLE APROACH TO SHIPBUILDING.

[66] United Nations. Paris Agreement. Technical report, 2015. URL https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[67] United Nations Environment Programme. *Recycling rates of metals*. 2011. ISBN 9789280731613. doi: ISBN978-92-807-3161-3.

[68] Klaas Van Dokkum. *Ship Knowledge*. DOKMAR, Maritime Publisers BV, Enkhuizen, The Netherlands, 7th edition, 2011. ISBN 9789071500183.

[69] Joost G. Vogtländer. *A practical guide to LCA for students, designers and business managers*. Delft Academic Press, Delft, 5th edition, 2017. ISBN 97890-6562-3614.

A
Yacht details - Confidential

B

Summary of conversations

B.1. Peter Schoneveld - Coordinator Yacht Services

In order to check the information that was gathered about the maintenance schedule and the moment for end of life, two conversations were held with Peter Schoneveld.

During the first meeting the information from figures 3.3 and 3.5 was discussed. For figure 3.3 I asked Peter Schoneveld if he saw anything that was remarkable in the figure and that could easily be explained. There were things that were further discussed, first all age groups have a large amount of dockings that have a duration of less than an month or 1-2 months. Peter explained that a docking to clean the underwater hull normally takes about a month. The second thing noticed by Peter was the even larger peak for short dockings for really young yachts, 0-5 years. This can be explained due to insurance work or small adjustments that take place after the yacht has been delivered. Finally the peak for all the age groups for a docking time between 5-6 months can be explained because this is the time needed for a full paint job.

The second discussion was about the slightly larger amount of older yachts that have a docking time that is longer than one year in figure 3.3 and the outcome of the research into second had prices shown in figure 3.5. [Confidential] . They look for this combination because the yacht will already have to be in a dock for 6 months to do a full paint job which is combined with the renewal survey. This means that both yachts will be around 20 years when the full refit is done. Yachts, in general, that undergo a refit after 20 years have quite an extensive list of activity's that will have to take place, Peter Schoneveld listed the following:

- New interior, the materials used in the interior are of out of fashion and need a update. But even is the owner is still happy with the design of the interior, it is often taken and and replaced with the exact same materials. This is because the materials already reached there life time.
- New AVIT and TV's, because technology is improving extremely fast and owners want to have the newest technology.
- New electrical cables, this is because of regulations. The wires are becoming more brittle over time and as soon as you touch a calbe after is has been in the yacht for more then 20 years you have to fully replace it.
- Extra systems to comply with new regulations.

Because this basically means that the yacht is stripped and only the casco and main machinery is kept, 20 years would be a good indication on the life time of a yacht according to Peter Schoneveld.

During the second conversation with Peter Schoneveld a discussion was held to get more detailed information on what exactly is replaced in a common refit that takes place after 20 years.

- Lighting and cables
- Equipment on the bridge
- All AVIT
- Interior, everything until the steel/aluminum is reached. This is actually often cheaper and more efficient.

- All copper piping and piping for salt water and vacuum systems plus the pipe insulation.
- All ventilation pipes
- Tubes for hydraulic systems
- Compressors for compressed air system
- Stabilizers are upgraded
- Exterior railings
- Fire detection and fighting systems
- Sewage system, because of compliance with MARPOL III
- Fresh water maker
- Windows
- Teak deck
- For pumps and machinery there is a term "RRR" meaning: Remove Repair Replace.

C
Diesel electric propulsion - confidential

D
Assumptions made on materials

Some materials that were used on yacht A were not found in the ecoinvent database. For this reason other options to assess these materials were investigated and adapted, as explained in this appendix. For all these materials further research into the composition and important substances with respect to the environmental impact should be conducted.

Mepla
Mepla is a material produces by Geberit for water piping. It consists of three layers, first modified polyethylene, aluminium and then another layer of polyethylene. Information on the thickness or the weight of the layers is not available. For this reason an analysis is done in Simapro to compare the impact of both materials. In figure D.1 it can be seen that aluminium has a larger impact on almost all impact categories. Since the specific weight of aluminium is larger then that of polyethylene , a plastic, Mepla will be modelled as only aluminium.

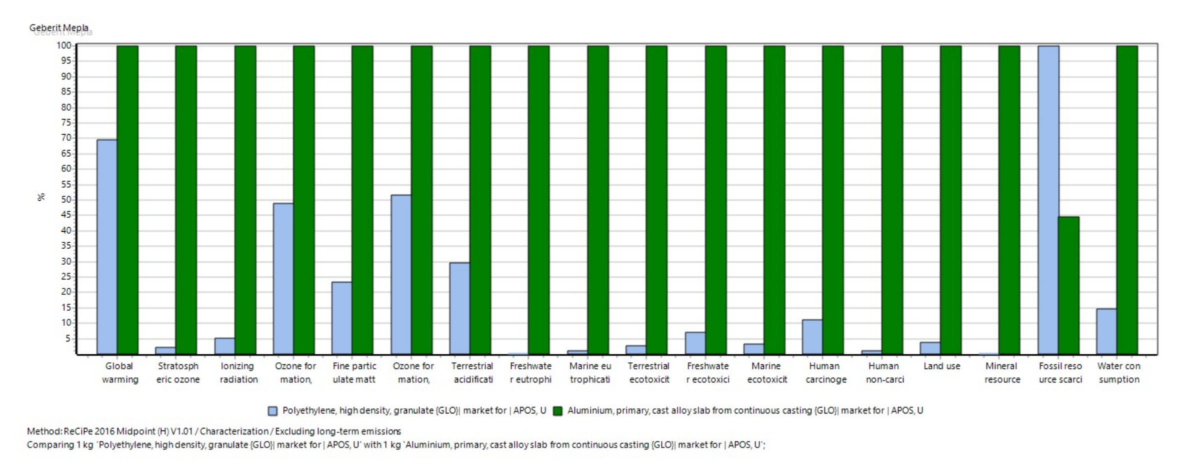


Figure D.1: Influence of polyethylene and aluminium

Epoxy paint
In order to protect and to make the surface more smooth a system of fairing and different paints is applied on the yacht. Fairing is only applied on the outside of the yacht but paint is used everywhere to protect the steel and aluminium structure. Based on the safety instructions provided by International paint for every epoxy paint an analysis is made of the paint substances in order to find which substances have a large impact. A comment has to be made that the safety instructions only provide the substances of which it is known to International paint that they have an impact on human health and the environment. These substances account of approximately 60 weight percent of the substances used in the paint.

However most substances could not be found in the ecoinvent database. The result was that only one of the paints, Epoxy GP, could be modeled. Epoxy GP coating is used as the base layer in the paint system and the substances are almost all in the ecoinvent database, only epoxy-propane is missing. However, the results when using Epoxy GP show a low impact from this paint. The impact was expected to be higher and because of this and the lacking information the paint substances it is assumed that it is modelled incorrectly.

Anti-fouling and cathodic protection
Anti-fouling itself is modelled as paint because no better information was available. The same goes for the cathodis protection.

Galvanized steel
Difference in impact could not be found in the ecoinvent database. The difference with regular steel is that galvanised steel is immersed in a zinc bath. Galvanised steel is modelled consisting for 1% of zinc and the other 99% of unalloyed steel.

Cunifer
Cunifer is a material that consists of 90% copper and 10% nickel and is modelled as such. (source, Feadship ship systems drawings)

Teak deck
Teak could not be found in the ecoinvent database but the material does appear in the idematt database. This database is created for the calculations of eco costs. With the information from the idematt database it is modelled as 95% Teak and 5% rubber.

Marble
Created in Simapro using information from the ecoinvent database and life cycle information on marble [29]

E

Life Cycle Inventory Assessment methods & impact categories

E.1. LCIA

A list of LCIA methods and a short description is provided in table E.1. The information is based on Handbook on LCIA [28] unless specifically said otherwise.

Assessment methods	Explanation
CML 2002	Dutch method that follows the ISO14040 series and gives the results at midpoint indicators. Normalization is an option but doesn't weigh the results.
Ecoindicator 99	This method was designed to simplify the interpretation of results and use a simple weighting method between midpoints. Because of the weighting this is a singe-indicator method meaning that all the different impact categories are added to each other.
ReCiPe 2008 or 2016	Is a follow up on Ecoindicator 99 and CML 2002 by integration of midpoints and endpoints in one framework. The data is updated from these earlier methods. Regional information is based on Europe. This methods has one of the biggest lists of substances that are taken into account.
EDIP2003	EDIP 2003 is a updated version of the EDIP97 which includes emission related impacts as well as resources and working environment. It is also possible to do an assessment based on regional, non global, information.
EPS 2000	The fist endpoint method which is designed to be used in combination with Monte Carlo simulations. Weighting can be added is a single score is desired.
LIME	A Japanese method which use Japanese regional information for categories that have local impacts. This method is mainly used in Japan.
LUCAS	Developed for use in Canada and uses regional data that is based on information from Canada.
TRACI	Was developed as a midpoint method based on the environmental conditions in the United States.
MEEuP	Method developed for the European Commission to evaluate whether energy using products comply with criteria for environmental labeling.
Eco cost	The eco cost method has been developed in the Netherlands and is based on the cost necessary to undo the damage to the environment caused by a product.

Table E.1: Overview of LCIA methods based

E.2. Impact categories

The effects that people, products, processes or businesses have on the environment are called environmental impacts. These impacts are subdivided into different categories and an overview based on the books Handbook on Life Cycle Assessment [28] & Life Cycle Impact Assessment [59] is given in table E.2.

Impact category	Explanation
Depletion of abiotic resources	Depletion of natural non living resources such as minerals and fosil fuels.
Depletion of biotic resources	Depletion of natural living resources such as plants
Land use	impacts on the resources aspect of land and the impact on biodiversity and life support functions.
Climate Change	Impact of anthropogenic GHG emissions on the radiative forcing of the atmosphere, resulting in a temperature rise.
Stratospheric ozone depletion	Impact anthropogenic emissions that result in the thinning of the stratospheric ozone layer. This results in a higher amount of solar UV-B radiation that reaches the earth and is harmful.
Human Toxicity	Impact of toxic substances in the environment to human health.
Ecotoxicity	The impact of toxic substances to aquatic, terrestrial and sediment ecosystems.
Photo-oxidant formation (Summer smog)	Photochemical oxidants are the product of an reaction of nitrogen oxides and non-methane volatile organic compounds(NMVOC). The main impact is caused by elevated tropospheric ozoneO_3 levels which are toxic for humans and plants.
Acidification	Acidification of soils and surface waters as a result of elevated sulphur (S) and nitrogen (N) deposition [16]. The main pollutants are NO_x, SO_2 and NH_x.
Noise	The impact of both underwater and above water noise.
Ironising radiation	Impact of radioactive substances and direct exposure to radiation.
Casualties	Impact to human life due to accidents.
Eutrophication	Impact of anthropogenic increase of nitrogen and phosphors that cause changes in the ecosystem due to over supply of nutrients.

Table E.2: Commonly referred to impact categories[28][59]

F

EPD & PCR

F.1. Environmental Product Declaration

The ISO has defined different types of Environmental Product declarations(EPD). Interesting are the type III environmental declarations which present quantified environmental information on the life cycle of a product on a voluntary base to enable comparisons between products fulfilling the same function[32]. The basis of these comparison is a LCA done according to the ISO14040 standards. A product that has an EPD has been assessed according to the standards, this does not mean that the product is sustainable. The objective of these EPDs are:

- To provide LCA-based information and additional information on the environmental aspects of products.
- To assist purchasers and users to make informed comparisons between products; these declarations are not comparative assertions.
- To encourage improvement of environmental performance.
- to provide information for assessing the environmental impacts of products over their life cycle.

In order to obtain an EPD the product has to be assessed according to a set of rules, requirements and guidelines which are specific for one or more product categories, these are called Product Category Rules (PCR). The PCR give more information on what should be included and excluded for the assessment of a product group. According to the ISO standard the PCR gives the specific rules for the use of a functional unit, system boundaries and all the other items listed in the scope definition of the ISO14040.

Since the PCR give an overview of what should be included in the LCA they are analyzed in order to get a sense of the difference between different products. There is a PCR for yachts but it is compared with other PCRs to get and idea of how inclusive the PCR for yachts is. Also the scope of this research is to keep calculations comprehensible to meet the requirements of the YETI. System boundaries are included in the PCR's and analyzed below because PCRs are one of few documents where system boundaries are actually written down. there is already a PCR for yachts, however no applications of this PCR are available yet, giving the perception that it is not a commonly used document. For this reason it will not be copied but analyzed and compared to other PCRs. Besides the PCR for yachts also the PCRs for transport in general, the PCR for passenger commercial airplanes and the PCR for buildings are analyzed. These are chosen because in the EPD system a yacht is part of the transport sector and the PCR is based on the standard PCR for general transport. The differences are thus showing were the yacht differs from general transport since it has the goal of providing luxury more than providing transport. The PCR of an airplane is chosen in order to look at the differences of an other capital intensive means of transport. Lastly the building PCR is included because of the hotel functionality of a yacht.
Most of these PCR are divided into upstream , core and downstream processes. Only the PCR of buildings is divided into more stages but these are linked to upstream , core and downstream processes in order to allow for comparison. The link between this division and the life cycle of a yacht is given in figure F.1. The system boundaries are given in table F.1 for the upstream processes, in table F.2 for the core processes, and in table F.3 for the downstream processes. The four most left columns represent the different PCR and indicate whether

an system boundaries is included (In) or excluded (Ex) in the PCR. If nothing is filled in, so an empty spot in the table, the PCR did not give clarity on that precise system boundary.

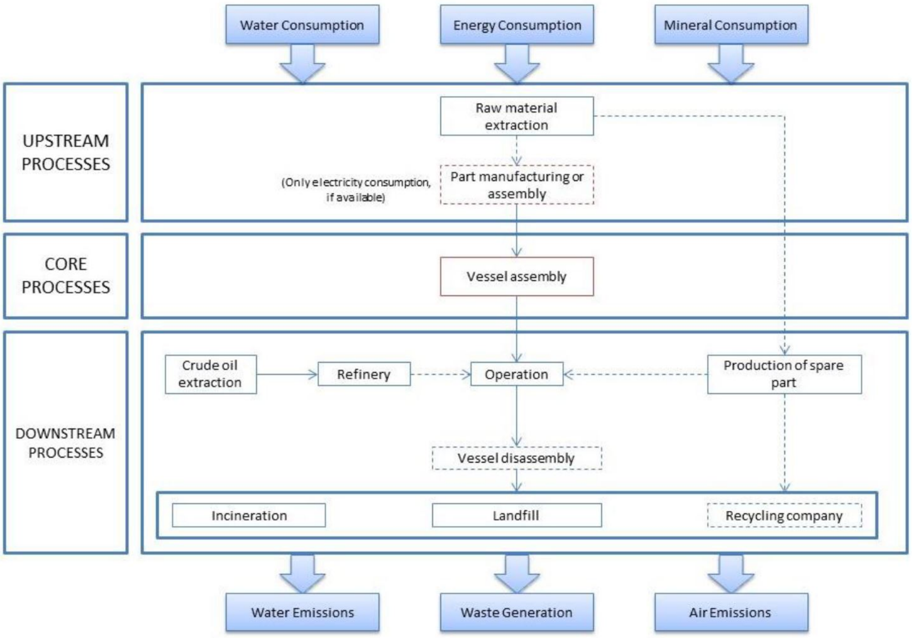


Figure F.1: Relation between deviation in processes and life stages, better picture is necessary

F.1.1. System boundaries of upstream processes

The system boundaries in table F.1 show that two system boundaries are the same for all the PCRs. The use of material and production of all main parts and components and the energy generation. The first one states that all the material used in the product has to be determined, also from product bought at suppliers. The generation of energy for main components requires information on the production process of suppliers of the yard. As most yard buy there main component and assemble it into a yacht it is hard to get this information.

The difference is mostly made in what is explicitly excluded. The upstream processes all take place at suppliers. Gathering information on all these processes would require a lot of work and time, which leaves two options: creating standard values or leaving the processes at suppliers out of the LCA.

F.1.2. System boundaries of core processes

Though the production of the different products is slightly different, the core process is considered the assembly of the product. The system boundaries are given in table F.2

There are three system boundaries that are included in all the PCRs, the assembly of the final product and the impact of the generation of energy needed for the core processes and the treatment of waste. Transportation to the core process and within the core process are mostly included. Including transport allows yard to have more influence on the result of the assessment of the production process. Including life cycles of used transport vehicles is not in line with the YETI requirement to keep the assessment understandable and to minimize effort.

The production of packaging is an interesting factor that requires some extra attention. Protection to equipment that is placed in a yacht before delivery is often done with a wooden box. The amount of wooden waste generated by De Vries is in weight by for the largest waste flow with 42%.

System boundaries are also defined in PCRs. For this reason three different PCRs are analysed(yachts[17], airplanes[13] and buildings[19]) together with the PCR framework for transport[3]. Use PCR!

1	2	3	4	System boundary
In	In	In	In	Extraction and production of raw material for all main parts and components
		In	In	Production of auxiliary products
		In	In	Production of semi products used in the core process
Ex	Ex	In	In	Production of packaging
In	In	In	In	Generation of energy used for the production of main components
	In			Transport to assembly plant
	In			Water consumption of tier 1 suppliers and or original equipment manufacturer
	In			Generation and treatment of waste at tier 1 suppliers and or original equipment manufacturer
Ex	Ex			Transportation of raw and basic materials to suppliers manufacturing plants
Ex				Production plants infrastructure life cycle
Ex				Suppliers manufacturing facilities infrastructure life cycle
Ex				Production, maintenance, dismantling and disposal of transportation vehicles
Ex				Transportation of maintenance materials and spare parts
Ex				Production of standard items for the commercial operation of the product (food, beverage, toiletry, towels etc)
	Ex			All infrastructure life cycle (EPD airplane) -> general boundaries: Exclude infrastructure en transportation life cycles.
	Ex			Production, maintenance, dismantling and disposal of vehicles used for transport
	Ex			Energy consumption for the production/assembly of parts by sub-tier-1 suppliers

Table F.1: Upstream system boundaries from different Product Category Rules
1. PCR for Yachts[17] 2. PCR for Airplanes[13] 3. PCR framework for transport[3] 4. PCR for buildings [19]

F.1.3. System boundaries of downstream processes

Though this research only focuses on the cradle to gate assessment the PCR's take into account the operational use as well. The system boundaries are shown in tableF.3 because the material use during the operational life phase of a yacht is still of interest for this research.
Because the life cycle of a building is given more detail to the use phase and the interest of this research is only for production, only system boundaries associated with maintenance, repairs and end-of-life are given in table F.3.

F.1.4. Other system boundaries

Boundaries towards nature
All PCRs define the boundaries to nature as the flows of material and energy resources from nature into the system. Emissions to air, water and soil cross the system boundary when they are emitted from or leaving the product system.

Boundaries towards time
The PCR for yachts and passenger commercial airplanes give a system boundary that the Life Cycle Inventory data is representative for a time of three years. This means that is you want to publish a EDP in 2019 the data should be representative for 2016, 2017 or 2018.

Boundaries towards geography
It is possible to limit the application of the use of the PCR to specific regions. A more commonly used geographical boundary setting is to require all data for the up, core and downstream processes to be representative for the site /region there the process takes place. In the PCR for yachts this requirement is only set for core processes meaning that for these processes location specific data should be used.

Boundaries towards other technical systems
This boundary comes forward in the framework for transport PCRs and is adopted into the PCR of yachts and airplanes. In all PCRs it indicates how to deal with recycled materials. The generator of waste is responsible

1	2	3	4	System boundary
In	In	In	In	Assembly of the final product
In	In	In	In	Impacts due to the production of electricity and fuels
In		In	In	External transportation to the core processes
In	Ex		In	Transportation inside the manufacturing site/plant
	In		In	Production and use of water consumed for final assembly of the product.
			In	All impact and aspects related to losses due to transportation (life cycle of products damaged during transportation)
Ex			Ex	Packaging of Yachts
In	In	In		Testing in own establishment
In		In		Maintenance activities to the machines used in production with varying extra requirements on frequency of the maintenance activity
	Ex			All infrastructure life cycle
		Ex		Manufacturing of production equipment, buildings and other capital goods
In	In	In	In	Waste treatment of waste generated during manufacturing
			In	Life cycle of product and materials lost during construction
Ex				Waste generated by employees
Ex	Ex	Ex		Business travel of personnel
Ex	Ex	Ex		Travel to and from work by personnel
Ex	Ex	Ex		Research and development activities
Ex			Ex	Manufacturing of production equipment, buildings and other capital goods

Table F.2: Core process system boundaries from different Product Category Rules
1. PCR for Yachts[17] 2. PCR for Airplanes[13] 3. PCR framework for transport[3] 4. PCR for buildings [19]

for that waste until it reaches a waste processing site. The user of waste or recycled material has to include the processing of the material and the transportation to it's production process. All the impacts of the material in earlier life stages are excluded for the user of waste or recycled material.

1	2	3	4	System boundary
In		In		Lifetime operation of the product EXCLUDE
In		In	In	End-of-life processes of the product after use
In	In	In	In	Maintenance and production of replacements/spare parts, during lifetime
	In		In	Transportation of spare parts or replaced parts (exclude in my research)
In		In		Transportation from manufacturing to retail or customer EXCLUDE since delivery to customer takes place at the yard
In				Transport to end of life facility/company EXCLUDE
	In			Fuel production for the operation of the product
Ex	Ex			Infrastructure (ports, harbours etc) life cycle
Ex	Ex			Treatment and disposal of waste generated from passenger during operation
Ex				Maintenance/Repair infrastructure life cycle
Ex				Recycling company infrastructure life cycle
Ex				Energy recovery from waste incineration
Ex				Yacht disassembly and waste treatment facilities infrastructure life cycle
Ex		In		End-of-life processes of packaging waste
	Ex			Consumables used during operation for the airplane (de-icing, lubricants)
	Ex			Non-revenue flights in/flight emissions
	Ex			Consumption of consumables during maintenance(lubricants, solvents...)
	Ex			Production of goods consumed by the passenger (Catering, food, potable water ...)
			In	Cleaning process of the product

Table F.3: Downstream system boundaries from different Product Category Rules
1. PCR for Yachts[17] 2. PCR for Airplanes[13] 3. PCR framework for transport[3] 4. PCR for buildings [19]