# Life Cycle Assessment of Boatbuilding Process with Ocean Plastic

Master's thesis in Production Engineering Master Program

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Department of Industrial and material science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

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Optimist hull with reclaimed ocean plastic produced at SSPA



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# ABSTRACT

In past decades, our ocean ecosystem was seriously damaged by increasing plastic pollution. To prevent further damage and manage ocean plastics, the 3Rs approach suggests to Reduce, Reuse, and Recycle waste. Current solutions include developing waste management systems, public awareness, and waste collection projects to reduce and recycle. However, reuse of reclaimed plastic in the industry is still limited. This paper presents findings from a study as part of the project Optimists För Havet, an ocean- cleaning campaign launched in 2018 with volunteers collecting marine debris along the Swedish west coast. Five Optimists with recycled ocean plastic from the campaign were produced at SSPA. To assess whether these Optimists are sustainable, the manufacturing process was evaluated based on a simplified life cycle assessment. A conventional boatbuilding process (without ocean plastic) was used as the control group for the comparative analysis.

The results show that the environmental impact of an Optimist with ocean plastic is higher than the one of the control group. Its Climate Change Ecosystems impact increases by 23.51% and for Human Toxicity, Ozone Depletion, Particulate Matter Formation categories, the respective increases are 21.51%, 32.87% and 5.57%. The energy consumed in production at SSPA is higher as well. Moreover, the Cycle Time of Optimists with ocean plastic is 230 hours, doubled compared with conventional ones. The main reasons for the negative results are the consumption of plastic consumables, increasing amount of raw material and longer lead time in the vacuum infusion process, which is required to fix ocean plastic fragments in the boat body since traditional manual lamination is unable to realize this. However, adapting processes and integrating recycled material must be highlighted as important industrial developments required to transition to more sustainable and circular production systems.

**Keywords:** Life cycle assessment; Environmental impact assessment; Ocean plastic; Sustainable manufacturing process; Marine pollution.

# PREFACE

This project is a Master Thesis within the Production Engineering Master Program at Chalmers University of Technology. This study has been conducted at the department of industrial and material science as well as SSPA, a sustainable maritime solution provider.

# ACKNOWLEDGEMENTS

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Furthermore, I would like to acknowledge John and Christian from SSPA, who gave me the access to all the data and information about the manufacturing processes in physical production to complete the life cycle impact calculations. A special thanks to Giada and students from Chalmers Material Lab for the knowledge of material processing processes. I would also like to thank all the different contacts who have provided me with information and data on the public campaign and raw materials.

Thanks to my parents and all my friends for always supporting me.

# NOTATIONS

LCA …… Life Cycle Assessment

LCI …… Life Cycle Inventory

LCIA …… Life Cycle Impact Assessment

GDP …… Gross Domestic Product

FMCG …… Fast-Moving Consumer Goods

PPE …… Polyphenylene Ether

PET …… Polyethylene terephthalate

UN …… United Nations

IPCC …… Intergovernmental Panel on Climate Change

GWP …… Global Warming Potential

CFCs …… Chlorofluorocarbons

HCFCs …… Hydrochlorofluorocarbons

UVB …… Ultraviolet B

PM …… Particulate Matter

ELCD …… European reference Life Cycle Database

JRC …… Joint Research Center

HDPE …… High-density polyethylene

LDPE …… Low-density polyethylene

PS …… Polystyrene

PA …… Polyamide

# CONTENTS

# 1. INTRODUCTION

## 1.1 Background

Only half a century after the massive production and spread of plastic production, plastic can be found everywhere in our daily life. This innovation of material brought us plenty of convenience with better performance and lower price. However, simultaneously, widespread disposable plastic products and poor management of plastic waste has resulted in serious plastic pollution globally. (Stuart J. Barnes, 2019).

In the ocean, as a sample, studies showed that the mean plastic debris accumulation was estimated at 1,794 items per square kilometer in Antarctic Peninsula area. (Ana L. d. F. Lacerda et al., 2019). Both macro plastics and microplastics can be found from various resource such as fisheries, commercial ships, recreational activities, ship cleaning etc. (Li Wai Chin, Tse Hin Fung, 2019). Marine ecosystem and marine animals suffered a lot from plastic pollution.

To save our ocean from deteriorating due to the plastic pollution, promotion of better waste management system and change of lifestyle are helpful in public domain in the long term. Additionally, there are several quick fix solutions to marine plastic pollution such as large-scale marine clean-up operations and beach clean-up campaigns to recollect ocean plastics. Over a 10-year period, 70320 tons of plastic debris is designed to be collected from the ocean. (Mateo Cordier, Takuro Uehara, 2019).

However, the question of how to deal with recycled plastic debris hasn't been properly answered yet. Nowadays recycled ocean plastic can be used in packaging and textile industry. But problems still lie in quality control and high investment etc.

By conducting life cycle assessment to defined manufacturing processes and comparing selected key impact indicators, the impacts of adapting ocean plastic in industrial manufacturing processes can be evaluated and analyzed.

Moreover, similar trade-offs may occur not only in selected manufacturing process with ocean plastic in this study, but also in other general production of products with recycled material. This study could provide instructions on how to eliminate the sustainability loss and maximize the positive impacts in future industrial application.

## 1.2 Aim

The aim of this study is to investigate the environmental impacts of applying reclaimed ocean plastic debris in manufacturing process.

Public usually believe that reusing plastic rubbish would definitely be a more sustainable way than burning or landfilling them directly. But is that true?

In common situations, the reusing of ocean plastic will change the conventional manufacturing methods, raw material and consumables. Thus, environmental impact of productions which involved marine debris would be different in various indicators.

With results from this study, strengths and weaknesses will be uncovered instead of blurred images. Those discoveries will contribute to the optimization of current manufacturing process as well as development of green products.

## 1.3 Objectives

In this project, a case study is supported by SSPA based on a campaign named Optimists För Havet. In Sweden, the campaign was launched in 2018. People were organized to clean several selected Swedish beaches. Rubbish collected were processed to explore more possibilities in in reusing in industry. At SSPA, Optimists with ocean plastic debris from Optimists För Havet were produced.

Therefore, objectives of this thesis project are life cycle assessments of manufacturing processes of Optimists with recycled ocean plastic.

## 1.4 Research questions

In order to achieve a holistic view of ocean plastic reusing in industrial applications, two research questions are raised:

a) How to measure the environmental impact of using ocean plastics in boatbuilding processes?

b) What are the environmental impacts of using ocean plastics in boatbuilding processes?

# 2. Literature Study

## 2.1 Ocean plastic pollution

Every year there are 5-13 million tons of plastic debris ends up in the ocean globally. (Håll Sverige Rent, 2019). Plastic rubbish may remain in the water for hundreds of years. Most of plastic debris found on the beaches are unidentifiable plastic items, disposable plastic bags and packaging.

In the upper ocean, the weight concentrations of ocean microplastics would be doubled by 2030 from the current situation based on a numerical model together with data from transoceanic survey, even including rubbish clean-up programs. (Atsuhiko Isobe et al., 2019).

These plastic invaders also reach the deepest part of the sea. In the Mariana Trench, a plastic bag was found at the depth of 10898 meters and 92% of plastic debris found below 6000 meters are disposable plastic products. (Sanae Chiba et al., 2018). The cleaning of deep-sea plastic debris could be more costly than upper ocean clean-up.

### 2.1.1 Consequences of ocean plastic littering

#### 2.1.1.1 Impact on animals and ecosystem

Tons of plastic floating in the ocean unfortunately put a threat on animals living in the ocean. Entanglement, ingestion and chemical contamination are three main risks caused by plastic debris. (Chris Wilcox et al., 2016). Once the ocean eco-environment is polluted by chemicals released from plastics, animals living on the land could be influenced as well since global ecosystem is dynamic. (Håll Sverige Rent, 2019).

#### 2.1.1.2 Plastic pollution costs money

Studies calculate that large-scale upper ocean clean-up projects would cost €492 billion-€708 billion, which equals to 0.7%-1.0% of the world GDP in 2017. (Mateo Cordier, Takuro Uehara, 2019). According to the Clean Europe Network, every year littering in Europe costs €25 per person. In Sweden, in order to clean the beaches full of ocean debris in Kosterhavet national park, government need to pay more than 1 million SEK each year. (Håll Sverige Rent, 2019).

The invisible part of cost is the waste of resource. It is possible to recycle and reuse them for longer lifetime, not just disposed after using.

#### 2.1.1.3 Plastic pollution has negative social impact

Plastic littering can lead to a negative spiral. Public would simply lose respect for a place where is polluted seriously and think it is totally okay to do the same thing. It will be harder and harder to draw public attention while situation is getting worse and worse.

### 2.1.2 Current proposals to reduce ocean plastic pollution

#### 2.1.2.1 Improvement of solid waste management system and raise of public awareness

Manage plastic rubbish properly is the most direct way to stop plastic debris from entering the ocean. Around 11%-13% of solid waste is plastic. (Romeela Mohee et al., 2015). Governments are supposed to build complete waste collection, transport and management systems. However, financial and political challenges still remain in lots of countries and regions.

By using environment friendly products instead of disposable plastic products, everyone can contribute to reduce plastic pollution. Moreover, education and training are essential to guarantee smooth running of solid waste management system. (Romeela Mohee et al., 2015). Social campaigns are helpful to gain sufficient public participation.

#### 2.1.2.2 Upper ocean and beach clean-up campaign

Collecting ocean plastic by conventional methods such as cleaning boats and nets are unrealistic under present situation since plastic debris has already been spread worldwide. Thus, more efficient methods with advanced techniques are urgently required.

Beginning in 2013, the Ocean Cleanup project created a passive system, which can capture plastic debris beneath the water surface with the power of ocean currents. In its scope, the passive system is estimated to remove 50% of the Great Pacific Garbage in 5 years at a relatively low cost. (The Ocean Clean Up, 2019).

Compared to the large-scale ocean clean-up project mentioned above, local beaches clean-up events are much closer related to everyone’s daily life. There are many societies, associations and projects that work actively worldwide. Not only for short-term clean-up, these campaigns also aim at long-term awareness of stopping supplying plastic to the ocean.

A project named Optimists För Havet is doing such thing in Sweden. On some of Swedish coasts, volunteers are engaged in marine litter collections on some of Swedish coasts and plastic debris collected from beaches was cleaned and processed in labs at Chalmers University of Technology for future reproduction. (Optimist för havet, 2019).

#### 2.1.2.3 Current applications of reusing ocean plastic in different industries

While the whole society is putting more efforts on reducing and recycling ocean plastic, the demand must follow. Presently, processed plastic debris from ocean are gradually adapted in some packaging and textile production.

In packaging industry, P&G , one of the biggest companies in FMCG industry, had launched the limited-edition Head & Shoulders shampoo bottle project with 25% beach plastic in France in 2017. After that they launched the second project which will produce the “Fairy Ocean Plastic” bottle made 100% from ocean plastic. (Heather Caliendo, 2018). Dell, the famous computer manufacturer, also managed to use recycled ocean plastic as part of their new laptop packaging system in 2017. By 2025, Dell intends to increase the annual use of ocean plastic 10-fold. (Karen Raubenheimer and Alistair McIlgorm, 2017).

In textile industry, a project named Waste2Wear from Holland is working on producing designer collections out of PET-bottles together with popular Dutch fashion brands. Their existing products include sportwear, workwear, fashion collection, basics and school uniforms. (Waste2wear, 2019). With a slogan FROM TREAT INTO THREAD, Adidas applies upcycled ocean debris in their athletic wear, football jerseys, tennis collections and swimwear. In the spring of 2019, Adidas released the world's first completely recyclable performance running shoe. They took a step forward as these shoes can be 100% recycled and used in reproduction. Therefore, no plastic waste will be created by the new product. (Parley, adidas, 2019).

Apart from packaging and textile industries, traditional manufacturing industries such as automotive industry, construction industry, marine industry etc. also acts as a major consumer of plastic. The demand of plastic products from massive production line could be much greater.

Some world's famous automotive brands have moved forward to explore the possibility of putting recycled plastic into their vehicles. For example, in the interior of Ford's car, the seat fabric contains about 22 plastic bottles. (Plastic make it possible, 2017). Meanwhile, BMW also has been working on adapting reclaimed ocean plastic into exterior panels and interior decorations for its electric-powered green cars. (Ray Massey for the daily mail, 2018).

### 2.1.3 Barriers and gaps in reusing ocean plastic

#### 2.1.3.1 The complex processing techniques before reusing

It is clear that ocean plastic cannot be used directly in production. R&D group, technical teams in those pioneering companies have to cooperate with external consultancy companies. Firstly, plastic debris needs to be cleaned, dried and sorted then followed by various processing, depends on the specific application. (Heather Caliendo, 2018).

#### 2.1.3.2 High financial investments

According to the vice president of global sustainability at P&G, the extra cost caused by reclaimed plastic will not be pass on to their customers. (Heather Caliendo, 2018). They claimed that what they did was for the environment and next generation. Behind this ambitious plan, companies must invest a lot in R&D and physical production. While some companies such as Dell believe they have made ocean plastic products economically feasible, there are still brands like Lewis that are worried about the future in the long term. (Heather Caliendo, 2018).

#### 2.1.3.3 Lack of standards and regulatory policies

As mentioned above, ocean plastic is playing its role in different industries, but current applications are relatively isolated. Different projects aim at meeting their own quality and safety requirements.

People keep working on cooperating between campaigns, countries and regions to develop unions as well as support common industry standards and regulations. (Waste2wear, 2019).

#### 2.1.3.4 The gap between industry and researches

Though many efforts have been devoted into ocean plastic clean-up, recycle and reuse in physical industry, there is a lack of environmental assessment for above actions. There is no doubt that removing the ocean debris from the water body has long-term positive impact on marine animals and ecosystem. However, while people are investing time, money and energy into industrial applications, it is also necessary to evaluate and visualize the impact of reusing ocean plastic from academic perspective.

By eliminating the gap, barriers mentioned above in reusing ocean plastic could be optimized. The visualization of environmental impact of reusing ocean plastic will find out the constraints in manufacturing processes therefore better sustainability performance can be achieved in future applications as well.

## 2.2 Life cycle assessment

### 2.2.1 Definition and purpose of life cycle assessment

The Life Cycle Assessment (LCA) is a comprehensive analytical tool that covers the analysis from different levels, including regional level, industry level, enterprise level and product/service level. (Ziyue Chen and Lizhen Huang, 2019).

As identified, a main purpose for manufacturers to apply LCA is to reduce to environmental impact of finished products. By checking the inputs and outputs, weaknesses might be uncovered then it is possible to improve the sustainability performance with clear targets. (Cameron Chai, 2014).

Moreover, LCA is commonly used not only at physical level, but also popular in enterprise management. Managers are motivated to use LCA in cognitive cases such as supporting business strategies and R&D.

### 2.2.2 Steps and tools in life cycle assessment

#### 2.2.2.1 Basic steps of life cycle assessment

Normally, LCA constitutes three steps: inventory analysis, impact analysis and improvement analysis. But the definition of goal and scope need to be done before starting to analyze material inventory. Boundary setting is critical in an LCA as well. (Cameron Chai, 2014).

With pre-defined boundary, the first step of LCA is making an inventory including raw material required, energy consumption, by-products or waste etc. (Cameron Chai, 2014). A life cycle inventory could be very detailed and contain lots of data. Therefore, the collection of data or information is significant and relatively time-consuming in this step. As the base of followed calculation, the inventory needs to be as precise as possible.

In the next step, the potential impacts on various aspects such as environmental, energy consumption etc. are calculated based on the life cycle inventory made previously. What's more, to support the assessment, reliable database and impact methods are important as well. Those LCA tools used in calculation will be introduced later.

With results from previous two steps, an optimization plan can be made based on identified weak points. If conditions permit, the LCA can be run circularly to verify whether the results from improvement plan are positive.

#### 2.2.2.2 Tools in a life cycle assessment

Open LCA, the platform, is an open source tool developed by GreenDelta in 2007 for LCA and sustainability studies. It provides a platform for life cycle modelling, parameter setting, calculation and analyzing. Results from OpenLCA can identify main drivers by process, flow or impact category. At the same time, it makes it possible to conduct costing and social assessment etc. As an open source platform, the choice of databases and impact methods are very flexible. The user can decide which database and impact method to use depend on specific case. These supportive tools can be imported to the software conveniently.

Another significant tool in the assessment is the LCA data base or sets. Usually an LCA database/set is organized by third-party organization. It contains a huge collection of elementary life cycle data.

As the calculating route, impact assessment methods are supposed to be used together with databases in the models built on the OpenLCA platform. The method identifies the calculation equations between every inputs and corresponding impacts.

## 2.2.3 Advantages and limitations of life cycle assessment

### 2.2.3.1 Key benefits of LCA

The scope of LCA could be very detail-focused and holistic. A systematic view is realizable depending on customer's requirements. Therefore, LCA can flexibly support a systematic study.

LCA can quantify inputs and outputs in a life cycle.

LCA has standardized format such as ISO 14040, which is widely used globally.

Apart from typical technical supports, LCA can be helpful in management and decision making as well.

### 2.2.3.2 Main limitations of LCA

The reliability, validity and accessibility of data matter a lot in an LCA. Therefore, LCA has high requirement on data quality.

Due to the possible gaps in real-life data collection, assumptions need to be made in most cases. This could make an LCA relatively subjective in some cases.

Where the LCA case happens decides the original and independent data resource. Sometimes it is hard to transplant an LCA case to another directly.

## 2.3 Boatbuilding methods in industry

### 2.3.1 Direct lamination method

Conventionally, this boatbuilding process shall be done by ship builders manually under normal indoor working environment without special accessorial equipment except universal tools. In a typical hand lay-up, reinforcements are laid into the mold and manually wet out using brushes, rollers or other means.

General steps of direct lamination are shown in below flow chart and the amounts of material are specified by the class rules. (Martinfruergaard, 2012).

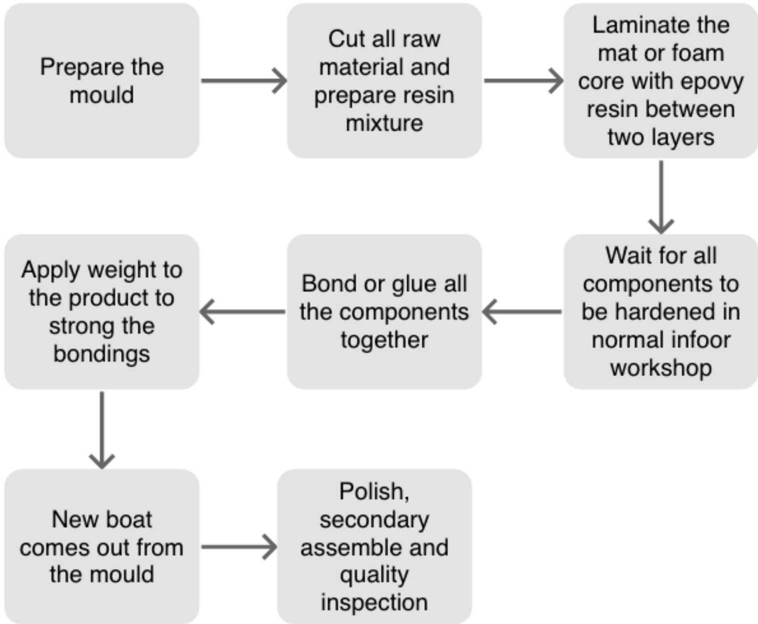


Figure 1. General manufacturing sequence of direct lamination boatbuilding method.

### 2.3.2 Vacuum infusion method

Due to the use of ground ocean plastic in production, traditional direct lamination cannot properly keep the fragment uniformly distributed around the Optimist body. A new boatbuilding method named vacuum infusion was introduced to the workshop.

The vacuum infusion process is a technique which uses vacuum pressure to drive resin into a laminate. In a vacuum infusion process, reinforcement materials are laid under dry state into the mold, then the vacuum will be applied before introducing resin. Once the vacuum environment is completed, resin will be literally sucked into the laminate through placed tubing. (Fiber Glast, 2019).

The biggest difference in vacuum infusion is that the epoxy resin will be applied in the end of whole process under the work of vacuum pump and heater except some pre-made small parts which are not included in the mould. (Compositeinteg1, 2013).

General processes of vacuum infusion are shown in below flowchart. In physical production, detailed infusion parameters may vary from workshops and working environment condition.

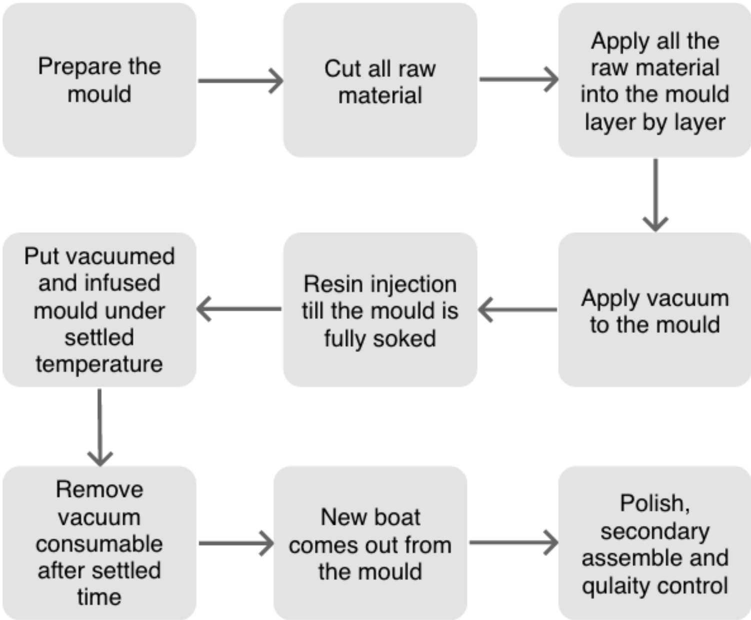


Figure 2. General manufacturing sequence of vacuum infusion boatbuilding method.

# 3. Methodology

## 3.1 Research method and case selection

### 3.1.1 Case study research method

As mentioned in the literature study, several pioneering companies have started their experimental or commercial project regards recycled ocean plastic. These real-life projects could provide this study with sufficient data sources.

From the background information, it is clear that why people decide to promote the reuse of recycled ocean plastics. Meanwhile the specific approach could vary from a case to another. One might not be able to represent the whole industry, but it is possible to transplant.

To answer the research questions:

a) How would the reusing of recycled ocean plastic influence the environmental impacts of manufacturing processes?

b) How to strengthen the value of reusing ocean plastic or eliminate the limitation?

Investigations into a contemporary case is necessary. Relevant data and information will be collected, and a life cycle assessment will be done to support further analysis and discussion.

### 3.1.2 Boatbuilding project at SSPA

Between 2018 and 2019, ocean plastic debris was collected by volunteers organized by Optimists För Havet. The recycled ocean plastic ended in the workshop at SSPA, a Swedish marine company and shipbuilder. Before arriving at SSPA, the ocean plastic was ready for being adding to the boatbuilding processes. The professional shipbuilders tried to use ocean plastic as a part of raw material in the manufacturing.

In SSPA, five dingles with ocean plastic were built. They varied from the amount, composition and color of additional ocean plastic. As shown at the cover page of this report, it is one of the five boats from SSPA. Pictures below show some other products in different color and types of recycled plastic debris.


Figure 3. Boats could vary a lot from color to the composition.

During this thesis project, the researcher stayed close to the workshop and collected the production data directly. Other information and data sources included raw material suppliers, Chalmers material lab and the campaign's organizer.

## 3.2 Definition of parameters in case study

### 3.2.1 Goal and scope of life cycle assessment

#### 3.2.1.1 Aim, objective and functional unit of life cycle assessment

The aim of the LCA is to compare two shipbuilding processes with different manufacturing methods and raw material inputs. Since this project is focusing on production phase of Optimists, sectional LCA suits the scope best.

In this study, the manufacturing process of dinghy in manufacturers' workshop will be the objective to investigate. The comparison is done between an Optimist with ocean plastic from Optimists för havet, Chalmers and SSPA and an Optimist made in conventional way, no specific manufacturer, but with processing data from several sources.

The functional unit in the LCA is a finished Optimist main body include an assembled hull, a gunwale, a centerboard case, a bulkhead and a mast step.

#### 3.2.1.2 General structured flow of boatbuilding processes

Figure 4 shows the general flows inside the production of the dinghy. This model will be specified in life cycle inventories later. The letter T refers to possible transportation.

Firstly, different raw materials go into the production, together with energy inputs. In some processes, there might be transport of the material, too. The details of production are not the same, but all finished boats are assumed to have the same level of performance.

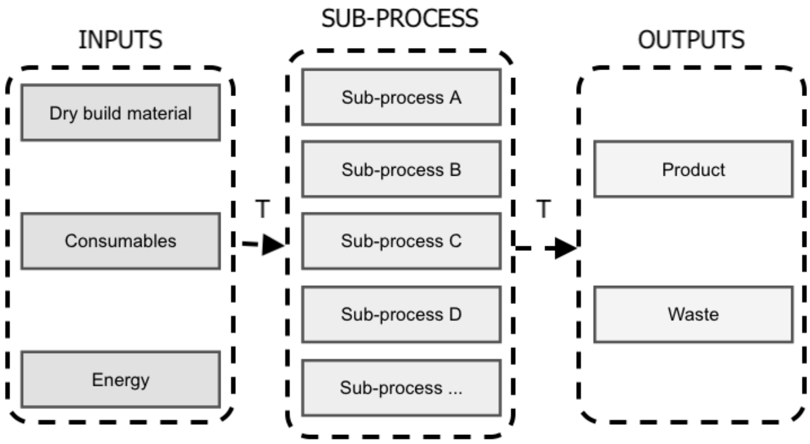


Figure 4. General structured flow of  boat building process.

### 3.2.2 Selection of life cycle impact categories

Since LCA is globally accepted under ISO 14040, the environment impact result should cover resource use, ecological consequences and human health. Under these three main categories, various detailed indicators can be selected flexibly.

In this study, following environmental impacts will be investigated.

**Climate change ecosystem**

Climate change can be defined as the change in global temperature caused by the release of greenhouse gas created by human activity. The raise of global temperature is expected to result in climatic disturbance, rising sea levels, desertification and spread of disease. Nowadays it is one of the most serious environmental problems to handle because of its large scale.

According to the UN's Intergovernmental Panel on Climate Change (IPCC), these climate change factors are expressed as Global Warming Potential over the time horizon of 100 years (GWP100), measured in the reference unit, kg $CO_2$ equivalent.

**Human toxicity**

The human toxicity potential is an index that reflects the potential harm of a unit of chemical released into the environment, and it is based on both the inherent toxicity of a compound and its potential dose. It can be potentially dangerous to humans through ingestion, inhalation or even contact. The impact category is measured in 1.4-dichlorobenzene equivalents.

**Ozone depletion**

Ozone-depleting gases damage stratospheric ozone or the ozone layer. CFCs, halons and HCFCs are the major causes of ozone depletion. Damage to the ozone layer reduces its ability to prevent UV light entering the earth's atmosphere, increasing the amount of UVB light reaching the earth's surface.

Developed by the World Meteorological Organization (WMO) and defines the ozone depletion potential of different gases relative to the reference substance CFC-11, expressed in kg CFC-11 equivalent.

**Particulate matter formation**

Particulate matter is a complex mixture of extremely small particles. Particle pollution can be made of a number of components, including acids, organic chemicals, metals, soil or dust particles. A multitude of health problems, especially of the respiratory tract, are linked to particle pollution in air. PM is measured in PM10 equivalents, which means particles with a size of 10um.

Apart from above indicators from LCA, some comparisons can be done directly according to the inventory.

**Energy consumption**

Energy consumption is the amount of energy or power used during the manufacturing processes. Electric energy consumption is the most common type used in industry.

**Cycle time**

Cycle time refers to the total time from the beginning to the end of a process. In this case, cycle time is the time period from the raw material entering workshop to the finishing of final products. (ISixSigma, 2019).

## 3.2.3 Selection of tools in life cycle assessment

### 3.2.3.1 LCA database

Since first released in 2006, the ELCD (European reference Life Cycle Database) provided LCI data from EU level and other source for materials, energy carriers, transport and waste management.

In this study, a latest version ELCD 3.2 was released in October 2015. Obvious errors in the original database from JRC (Joint Research Center) were corrected including some missing datasets, elementary flows were mapped to OpenLCA reference list and some refactoring in categories was conducted.

The respective datasets are officially provided and approved by corresponding industry associations. Now JRC is taking actions to review datasets and increasing data quality. All process datasets are in line with ISO 14040 and 14044 as stated by data's own providers.

Datasets in ELCD can be used free of charge and also distributed to third parties. (OpenLCA Nexus, 2019).

### 3.2.3.2 Life cycle impact assessment method

LCIA (Life cycle impact assessment) method is the tool that translates emissions and resource extractions into a limited number of environmental impact scores. ReCiPe is one of those methods for LCIA in an LCA study.

There are two mainstream ways in ReCiPe to derive environmental impact scores: at midpoint or endpoint level.

Midpoint level indicators focus on single environmental problems while endpoint indicators show the environmental impact on three higher aggregation levels: effect on human health, biodiversity and resource scarcity. Converting midpoints to endpoints simplifies the interpretation of the LCIA results. (RIVM, 2011).

In this case, ReCiPe endpoint method is used, and four indicators as stated above are used for quantifying the environmental impacts.

## 3.2.4 System boundary

LCA in this study has a limited boundary with a focus on the cradle phase of Optimists. Raw material, energy consumption, possible transport and in-house waste management are included inside the boundary. Therefore, the use and grave phase of Optimists will not be concluded in this LCA.

**Geographical circumscription**

The manufacturing process of Optimist with ocean plastic is taken place in Gothenburg, Sweden. To make proper comparisons, the location of traditional shipbuilding process will be at the same place.

**Time scale**

The boat with ocean plastic was built during the winter season between 2018 and 2019. For the same reason, the production of normal ships will be set in the same season.

**Intangible by-products of the production**

Any intangible by-products produced in the manufacturing process will not be considered in this LCA.

### 3.2.5 Limitations and assumptions

**Limitations**

In an LCA study, waste management usually refers to the waste management after usage stage of product. Here in this case, since the usage phase is not included in the scope, waste management mentioned in the following report will only cover the waste produced by manufacturing processes.

Transport from suppliers to SSPA and after production will not be included in this assessment due to the difficulties in data collection of the direct lamination method. At the same time, in-house transport will not be taken into calculation either cause the workshop has a very limited space (30 sqm). Moreover, since this LCA study has a scope which focuses on the manufacturing phase, the transport in waste management (from factory to incineration station) will be excluded.

**Assumptions**

Totally there were five Optimists built in SSPA and the amount of used ocean plastic differed among them. To control the total weight and infusion quality, the amount of raw material and consumables changed with the ocean plastic, too. the data used in this study is from the No.3 boat built in SSPA. Since it was the first time for SSPA to use recycled ocean plastic in manufacturing, our professional shipbuilder believed that from the third ship, the method and product were more stable and reliable.

Though boats produced by two manufacturing methods have different appearance and compositions, the experienced shipbuilder assumed that these differences have little influence on Optimists’ performance. Differences in performance would be very small because the method of construction is only one factor of many.

In project Optimists för havet, collected marine plastic rubbish has complex compositions since it is mixed with plastic bottles, plastic bags, packaging plastic etc. After primary sorting and cleaning in Envir and pre-treatment at Chalmers material lab, the composition of mixed reclaimed plastic particles is assumed to be 65% HDPE, 30% LDPE and 5% PS, according to Angelica and Alexandra, who operated the treatment in labs before ocean plastic coming to SSPA.

## 3.3 Data collection

### 3.3.1 Principles of data collection

For the Optimist with ocean plastic, data for the detailed manufacturing processes will be collected from SSPA. Information of raw material and ocean plastic are from suppliers and Chalmers material science lab.

For the normal Optimists, manufacturing data will be collected from different sources including production data from experienced ship builders.

Generally, for two manufacturing processes, data about emissions, transport, waste management etc. will be taken directly from the LCA database.

All the data and information used in this case are from legal sources including scientific publications, published books, and websites which are official and trustworthy. Also, some data and information are collected from personnel such as shipbuilders from factories and scientists from the university who have abundant knowledge in shipbuilding or material science field.

### 3.3.2 Pre-treatment of ocean plastic before manufacturing

According the project manager from SJÖRÄDDNINGS SÄLLSKAPET, during 2018, the Optimists För Havet had about 10 clean-up-events at 4 specially chosen stations in Sweden. Attendants (the public) made the clean-up of beaches and at the same time plastic debris was sorted from other littering. From these 10 events, totally around 32 cubic of littering was collected and 9 of them were plastic. Afterwards, 6.5 cubic containing hard plastic was sent to Envir, a company which is specialized in waste composition analysis. Envir had the mission to sanitize and sort the plastic into different types (PPE, PET and so on). Then those cleaned plastic was sent to Chalmers material science lab, where the plastic debris from project Optimists För Havet was sorted, cleaned again and hardened for SSPA.

For shipbuilding, there is a general international Optimists class rules for both professional and amateur builders. According to the international Optimist class rules, an Optimist should be a One-Design Class dinghy. Ships of this class should be in hull form, same construction throughout, controllable weight and weight distribution. No matter what manufacturing process is used, all parameters such as dimensions / materials / functional components etc. should follow the rules except specifically allowed variations. International Optimists class rules. (International Optimist Dinghy Association, 2018).

### 3.3.3 Life cycle inventory

Since different manufacturing methods and raw material were used in production at SSPA, inputs and outputs of two boats varied a lot. The general flow chart will be specified of each Optimist individually. Production inputs, outputs and manufacturing technique will be introduced in this chapter.

3.3.3.1 Optimists building processes in SSPA with Vacuum infusion method

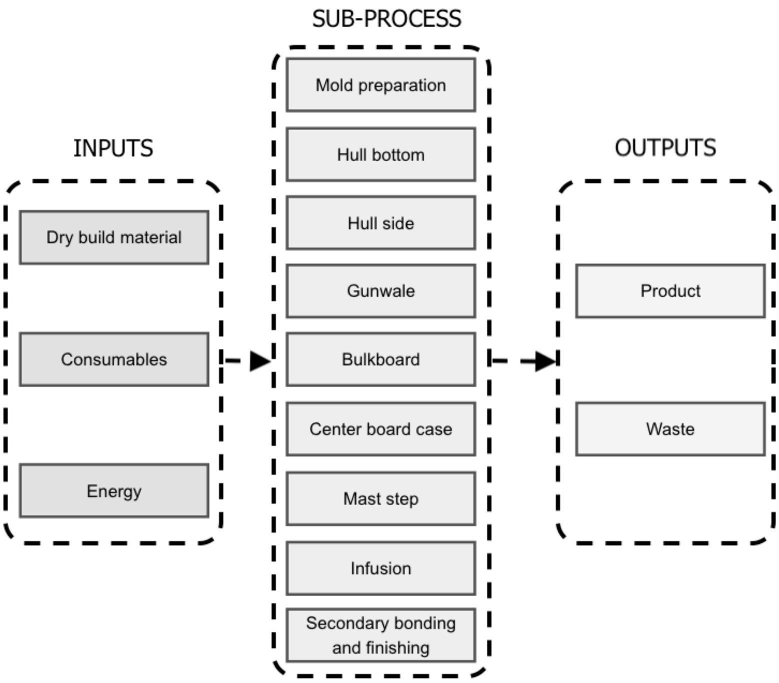


Figure 5. Flow chart of life cycle in vacuum infusion process.

**Input material flows**

Since the manufacturing process is complex, it might not be clear enough to state all elements in the flow chart. Therefore, the complete inventory data will be shown in following Table 1. For detailed inventory data of each sub-process, see Appendix A.

Table 1. Overall input material flows inventory of vacuum infusion process.

| Input material flow | Amount (g) |
|---|---|
| Glass fiber | 9102 |
| PET | 2060 |
| Pan fiber veil | 472 |
| Epoxy resin | 24470 |
| Paraffins | 30 |
| PS | 116.3 |
| HDPE | 4301.9 |
| LDPE | 1160.8 |
| Synthetic Rubber | 425 |
| Dimethyl Ether | 15 |
| Acetone | 15 |
| Propanol | 1692 |

| | |
|---|---|
| Butanol | 376 |
| PA | 255 |
| Silica | 525 |
| Water | 1692 |

**Vacuum infusion process**

In Figure 6, the general sequence of steps that comprises the vacuum infusion process is introduced. Generally, the whole process is divided into 7 main events. Detailed information will be stated step by step for the shipbuilding process in this project.

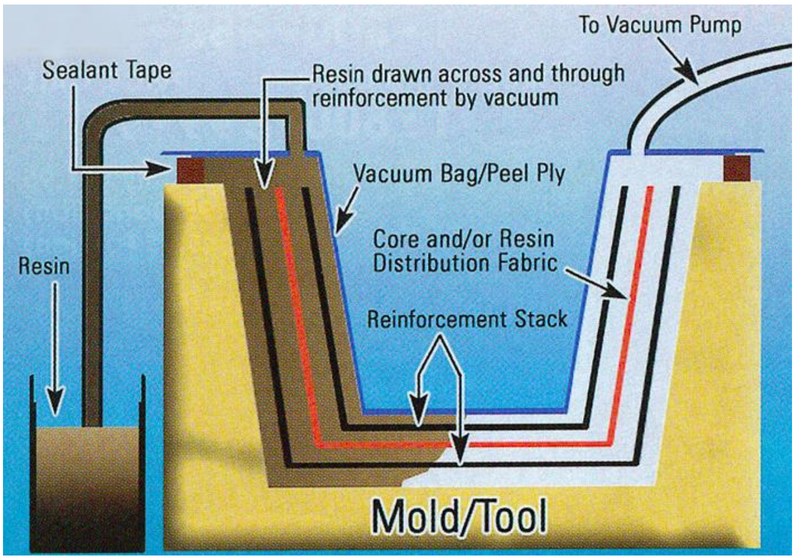


Figure 6. Schematic diagram of vacuum infusion process in SSPA, (Redback Aviation, 2018).

Step 1:

After proper cleaning of the boat mould, apply mold release agent to it. Then apply the chosen reinforcements. For boat in this case, glass fiber, pan fiber veil, PET foam core and the reclaimed ocean plastic are selected. They are applied into the mold in sequence.

Figure 7. Apply reinforcement (glass fiber roving).

Figure 8. Applying reinforcement (PET foam core and surface mat).

In this vacuum infusion process, resin enters the mold from several fixed points. However, resin will always travel in the path with smallest resistance. The great resistance in reinforcements can prevent resin flow. Therefore, applying the resin transport medium is very important to get an even infusion.

Figure 9. Applying resin transport medium.

Step 2:

As mentioned above, resin will be fed into the mold from fixed points. Apart from the using of resin transport medium, resin feed lines are required for vacuum infusion as well.

Spiral tubing used in SSPA is a plastic ribbon which is coiled into a tube shape. Air or resin can enter or leave the walls of the tube throughout its entire length. Spiral tubing needs to be wrapped in peel ply for easy removal later.

In vacuum infusion process, spiral tubing is also an ideal choice as it works well both for air and resin. Therefore, in SSPA, shipbuilder applied spiral tubing for two purposes. It works as vacuum lines first, then acts as resin feeding line after vacuum is applied.

Figure 10. Design and installation of resin feeding/vacuum lines.

Step 3:

The vacuum bag should be tight, but still allow enough room for other materials such as the network of tubing. Attach the vacuum bag to the mold by sealant tape comprehensively and be careful with tubing to avoid leakages.

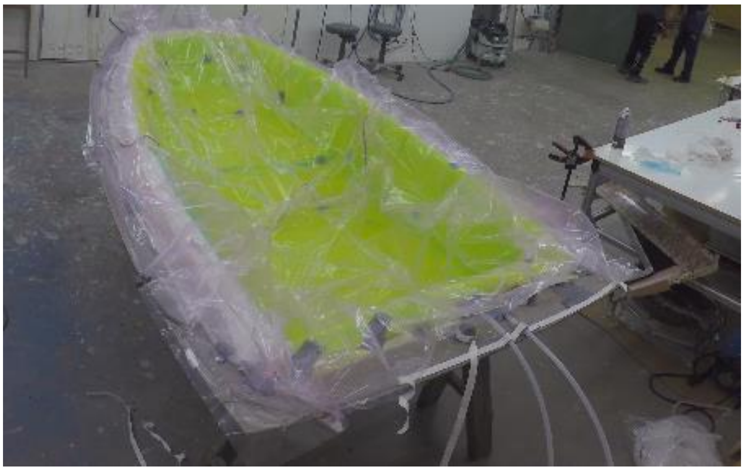

Figure 11. Building and attaching/sealing the vacuum bag to mold.

Step 4:

Attach the vacuum pump. In the vacuum infusion process, resin is infused under vacuum pressure.

After switching the vacuum pump on, it is time to keep an eye on any possible leak. A leak detector is helpful to discover small leaks. Even a tiny leak can influence the product quality or even ruin the part completely.

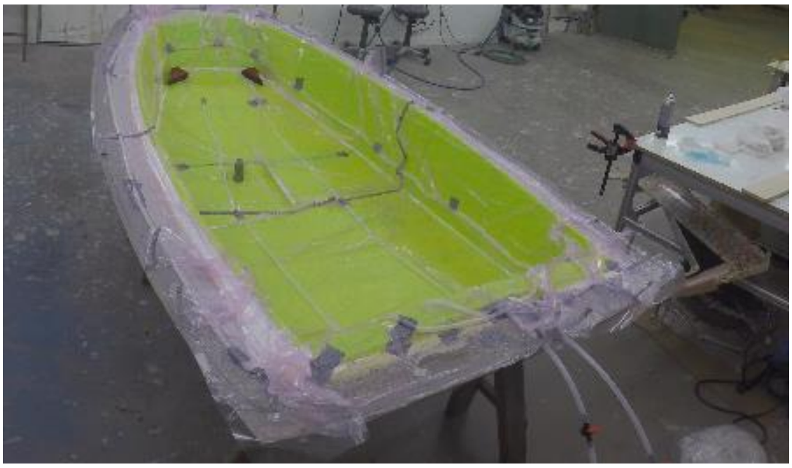

Figure 12. Vacuuming mold together with reinforcement.

Step 5:

There is no specific special resin required for vacuum infusion. Any resin can be used for infusion. Usually, the shipbuilder decides the type of resin depending on viscosity and other parameters. In shipbuilding process at SSPA, epoxy nm 650 was chosen for its low viscosity.

Step 6:

Once everything is in place and ready to start, the resin inlet can be unclamped. Resin will be quickly sucked through the network of tubing and dry materials. In this step, the resin should be visibly moving in the mold.

When the lamination is wet out completely, no more resin is needed, then it is time to clamp off the resin supply. However, keep the vacuum pump working until the resin has fully gelled. In SSPA, industrial heater was used to achieve the required temperature for better quality.

Step 7:

Remove all consumables and get the part out of mold. Grind corners and excess material. Finish the secondary bonding and quality inspection.

Figure 13. Finished product at SSPA.

**Waste management**

The main source of manufacturing waste is excess material from reinforcement because the mold has fixed dimension and dry reinforcement needs to be cut to fit the mold. In production at SSPA, 10% of dry build materials are counted as wasted.

Moreover, Due the property of vacuum infusion process, consumable materials are used during infusion. Once the part is finished, those consumables are useless and unfortunately most of them are unable to be reused. In SSPA, 6% of all materials are counted as wasted.

During infusion, partial resin will be taken by resin transport medium and this part will be treated as waste as well. Refer to the technical characteristic of resin transport mat, 666g resin will be absorbed per square meter.

Table 2. Amount of wasted epoxy resin taken by consumables.

| | Area (square meter) | Amount (g) |
|---|---|---|
| **Wasted resin from infusion** | 5 | 3330 |

Overall amount of waste from production in different categories is shown below.

Table 3. Waste from vacuum infusion process.

| Waste from production | Amount (g) |
|---|---|
| Glass fiber | 910 |
| PET | 206 |
| Pan fiber veil | 47.5 |
| Epoxy resin | 3388.5 |
| HDPE | 167.5 |
| LDPE | 31 |
| Synthetic Rubber | 25.5 |
| PA | 15 |
| Silica | 31.5 |

At SSPA, rubbish from production will be sorted into metal and others including plastic waste. According to the same reason, currently there is no recycling of plastic waste inside the factory. That waste will be collected and sent to nearby garbage incineration station.

**Energy consumption**

In the manufacturing process of Optimists, according to SSPA, the major energy consumption is electricity. Others such as water, can be ignored.

Commonly it is more precise to use real production data in calculating energy consumption. However, in this case, electricity consumption in SSPA is counted in total. The whole workshop is a connected system. Electricity used for a boat is nearly zero compared to overall factory.

Moreover, in vacuum infusion process, the main electricity consumers are vacuum pump and industrial heater used during curing phase. Other equipment such as grinders or glue guns are universal and have similar usage in both vacuum infusion and direct lamination. It is not practical to take these tiny consumptions into consideration.

Therefore, the electricity consumption will be calculated by figures provided by vacuum pump and industrial heater suppliers and shipbuilders. Detailed calculations can be found in Appendix B.

Table 4. The amount of electricity used in one boat built in vacuum infusion process.

| **Electricity consumption of main electricity consumer (KW*h)** | |
|---|---|
| Vacuum pump | 90 |
| Industrial heater | 360 |
| Total | 450 |

**Cycle time**

Data of cycle time for one boat in SSPA was directly collected from workshop recording. The manual work time for a boat with ocean plastic are 50 hours and the heating treatment requires 180 hours. In total, the cycle time of an Optimist built in vacuum infusion process is 230 hours.

3.3.3.1 Conventional boatbuilding processes with direct lamination method

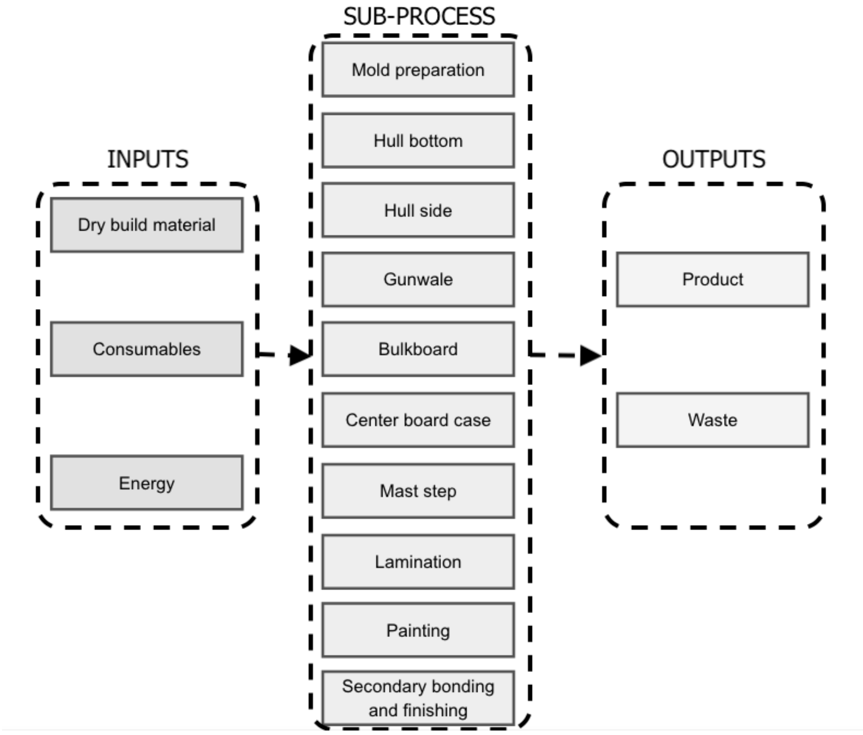


Figure 14. Flow chart of life cycle in direct lamination process.

**Input material flow**

Overall inventory is shown in following Table 5.

For detailed inventory of each sub-process, see Appendix C.

Table 5. Overall input material flows inventory of direct lamination process.

| Input material flow | Amount (g) |
|---|---|
| Glass fiber | 7933.5 |
| PET | 1900 |
| Carbon fiber | 725 |
| Epoxy resin | 22432 |
| Acetone | 3175 |
| Propanol | 1692 |
| Butanol | 376 |
| Silica | 525 |
| Water | 1692 |
| Dimethyl ether | 15 |

**Direct lamination process**

As mentioned in methodology chapter, reinforcements are laid into the mold and manually wet out using brushes, rollers or other means in a typical direct lamination.

Step 1:

After proper cleaning of the boat mold, apply mold release agent.

Figure 15. Getting the mold prepared, (Martinfruergaard, 2012).

Step 2:

Usually polyester resin is chosen for direct lamination. In this study, acetone is selected as the lamination solvent.

Step 3:

According to the international Optimist class rules, glass fiber roving, woven cloth and PET foam core are selected as designated reinforcement. They will be applied in the sequence referred to the class rules.

Figure 16. Applying reinforcement to the mold, (Martinfruergaard, 2012).

Step 4:

Once a layer of reinforcement is placed, shipbuilders need to apply the resin mixture to the surface of reinforcement thoroughly. Then a significant and time-consuming work is releasing potential air bubbles and smoothing corners/seams by rollers and other tools as best as they can.

Figure 17. Manual lamination process, (Martinfruergaard, 2012).

Figure 18. Laminating the corners/seams, (Martinfruergaard, 2012).

Step 5:

Iterate step 3 and 4 until all reinforcements are finished

Step 6:

Paint the outside surface of part. In the international Optimist class rules, the painting of Optimist is optional. But most shipbuilders would choose to paint it for better exterior appearance.

Step 7:

Wait for laminated part to be cured. Normal Optimists can be cured at room temperature. Therefore, in this step those laminated parts will be cured in the workshop without any heating equipment.

Step 8:

Assemble body parts together. Body hull, gunwale and other main constructions are glued together manually. By applying force through the mold structure, the bonding will be stronger.

Figure 19. Gluing parts together, (Martinfruergaard, 2012).

Figure 20. Strengthen of the bonding, (Martinfruergaard, 2012).

Step 7:

Remove all consumables and get the part out of mold. Grind corners and excess material. Dimension check and quality inspection.

Figure 21. Grinding and polishing, (Martinfruergaard, 2012).

Figure 22. Finished product / Quality inspection, (Martinfruergaard, 2012).

**Waste management**

Similar to vacuum infusion process, there are excess materials as the major waste from manufacturing. Therefore, 10% of dry build materials are counted as wasted.

In normal Optimist building process, even the amount of used consumable materials is much less than vacuum infusion process, waste still existing. So, 6% of material cost is consumables.

Table 6. Inventory of waste from production.

| Waste from production | Amount (g) |
|---|---|
| Glass fiber | 793.5 |
| PET | 181 |
| Carbon fiber | 72.5 |
| Epoxy resin | 1344.5 |
| Acetone | 190 |
| Silica | 31.5 |

In traditional shipbuilding process, there is no recycled ocean plastic. In this study, to make the comparison more convincing, the same amount of ocean plastic as used in vacuum infusion process is treated as waste in direct lamination.

Table 7. Amount and composition of ocean plastic used in production.

| Composition of ocean plastic (g) | | |
|---|---|---|
| HDPE (65%) | LDPE (30%) | PS (5%) |
| 1511.9 | 697.8 | 116.3 |

The total amount of ocean plastic for calculation is 2326g.

To make proper comparisons between two manufacturing processes, the direct lamination process is set under the same physical environment as vacuum infusion process. Therefore, there is no recycling of waste either. They will be sent to incineration station as well (include the ocean plastic).

**Energy consumption**

As described in above general steps, no special equipment like pump or heater are required by direct lamination process. Basically, electricity is consumed by universal tools and illumination of workshop. Therefore, in this situation electricity consuming data is difficult to get for the same reason as stated in vacuum infusion process.

**Cycle time**

Cycle time of conventional boatbuilding process can vary a lot between different manufacturers especially the waiting time, which depends on the manufacture procedure said by operators at SSPA. For instance, the gel coat can be applied into the mold at the end of a day. Then cure time is long enough for lamination the next day and none need to wait during daytime. However, in common situation, time plan is hard to be so perfect. According to operators’ experience, the waiting time each boat in direct lamination could be approximately 100 hours. The manual work time are 25 hours. In total, the cycle time of an Optimist built in direct lamination process is 125 hours.

## 3.4 Life cycle impact calculation

In chapter 3.2, the scope of life cycle assessment is defined and the tools for life cycle assessment are selected. Together with data from above life cycle inventory, the life cycle impact can be calculated by following the model shown in Figure 23.

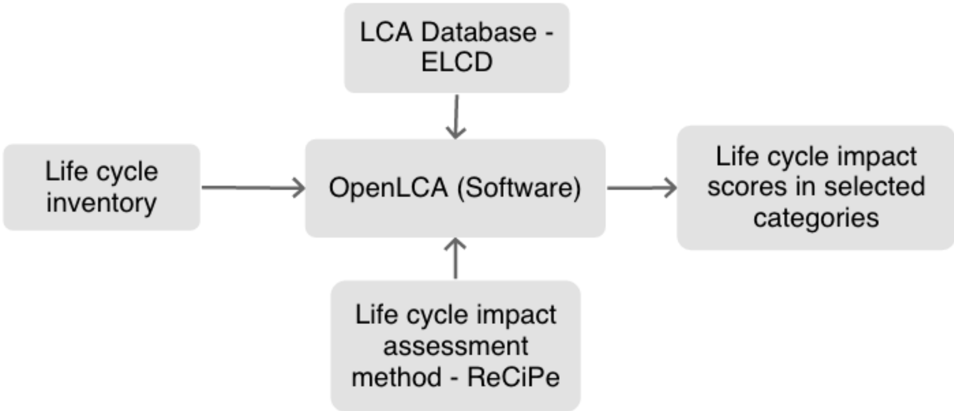


Figure 23. Calculation model of life cycle impact in selected categories.

In this study, the software OpenLCA acted as a platform for the calculation. Input data is from the life cycle inventory of the boatbuilding processes. Each input will find a corresponding raw material flow inside of the LCA database and the life cycle impact assessment method will transfer them into scores in selected environmental impact categories. The final results will be the summary of score of each input in separated indicators.

# 4. Results

In this study, the life cycle impacts scores were assessed in 6 categories. In this chapter, the environmental impact scores of each boatbuilding processes will be presented first and then be compared to each other. Additionally, the consumptions of energy/cycle time/impacts of waste handling and effect on human health will be interpreted.

## 4.1 Life cycle impact results of vacuum infusion with ocean plastic

### 4.1.1 Environmental impact of main manufacturing process

Table 8. Environmental impacts of two manufacturing methods in selected indicators.

| | Climate change ecosystem | Human toxicity | Ozone depletion | Particle matter formation |
|---|---|---|---|---|
| Vacuum infusion | $9.07368E^{-7}$ | $1.20837E^{-5}$ | $6.33864E^{-9}$ | $1.31755E^{-5}$ |

### 4.1.2 Environmental impact of waste management

Table 9. Environmental impacts of waste treatment.

| | Climate change ecosystem | Human toxicity | Ozone depletion | Particulate matter formation |
|---|---|---|---|---|
| Vacuum infusion | $-\ 2.08140E^{-7}$ | $-\ 6.03071E^{-6}$ | $-\ 5.89570E^{-11}$ | $-\ 4.97871E^{-7}$ |

While calculating the impacts of manufacturing waste, input flows were selected from category: end-of-life treatment/incineration/energy recycling, which means they are sent to incineration station and finally transformed into recycled energy.

### 4.1.3 Environmental impact of energy consumption

Due to the difficulty in data collection in physical production, the consumption of Vacuum infusion is calculated according to the equipment technical information. Values for illumination and universal tools are treated as the same in two production method. In this case, only the different part will be taken into consideration.

The electricity consumption of vacuum infusion process is 450 KW*h. It was calculated according to the working hour and the technical power data from equipment.

Table 10. Environmental impacts of electricity consumption in vacuum infusion process.

| | Climate change ecosystem | Human toxicity | Ozone depletion | Particulate matter formation |
|---|---|---|---|---|
| Vacuum infusion | $1.93565E^{-5}$ | $5.7515E^{-5}$ | $4.24476E^{-9}$ | $1.80672E^{-5}$ |

In this case at SSPA, the input energy flow is set as electricity from waste incineration – waste incineration of unspecified plastics in municipal solid waste (at plant, average European waste-to-energy plant, without collection, transport and pre-treatment).

### 4.1.4 Production efficiency

The cycle time of an Optimist built in vacuum infusion process is 230 hours.

## 4.2 Life cycle impact results of direct lamination without ocean plastic

### 4.2.1 Environmental impact of main manufacturing process

Table 11. Environmental impacts of two manufacturing methods in selected indicators.

| | **Climate change ecosystem** | **Human toxicity** | **Ozone depletion** | **Particle matter formation** |
|---|---|---|---|---|
| Direct lamination | $7.34664E^{-7}$ | $9.94408E^{-5}$ | $4.76695E^{-9}$ | $1.24809E^{-5}$ |

### 4.2.2 Environmental impact of waste management

Table 12. Environmental impacts of waste treatment.

| | **Climate change ecosystem** | **Human toxicity** | **Ozone depletion** | **Particulate matter formation** |
|---|---|---|---|---|
| Direct lamination | - $2.21509E^{-7}$ | - $1.87819E^{-6}$ | $4.60685E^{-11}$ | - $1.01171E^{-7}$ |

While calculating the impacts of manufacturing waste, input flows are selected from category: end-of-life treatment/incineration/energy recycling, which means they are sent to incineration station and finally transformed into recycled energy. From the results, production waste treatment has positive impacts in selected categories except Ozone depletion in Direct lamination.

### 4.2.3 Environmental impact of energy consumption

Due to the difficulty in data collection in physical production, values for illumination and universal tools in two boatbuilding processes are treated as the same. In this case, only the different part will be taken into consideration. For better efficiency and clearer comparison, the energy consumption of direct lamination process will be ignored, which does not mean there is no energy consumption in it.

### 4.2.4 Production efficiency

The cycle time of an Optimist built in direct lamination process is 125 hours.

## 4.3 Comparison of two boatbuilding processes

### 4.3.1 Comparison of environmental impacts of main manufacturing process

Table 13. Environmental impacts of two manufacturing methods in selected indicators.

| | **Climate change ecosystem** | **Human toxicity** | **Ozone depletion** | **Particle matter formation** |
|---|---|---|---|---|
| Direct lamination | $7.34664E^{-7}$ | $9.94408E^{-5}$ | $4.76695E^{-9}$ | $1.24809E^{-5}$ |
| Vacuum infusion | $9.07368E^{-7}$ | $1.20837E^{-5}$ | $6.33864E^{-9}$ | $1.31755E^{-5}$ |
| Difference | $+1.72704E^{-7}$ | $+2.13912E^{-5}$ | $+1.57169E^{-9}$ | $+0.6946E^{-6}$ |

From the values shown in Table 13, the environmental impacts of two manufacturing processes are close but basically the boat containing recycled ocean plastic has higher impact on environment than traditional one.

**Climate change ecosystem (GWP100):**

For each boat, the $CO_2$ emission of production with ocean plastic and vacuum infusion process increases by 23.51% compared to direct lamination shipbuilding without ocean plastic.

**Human toxicity:**

The potential harm to the human body from released chemicals would increase by 21.51% if manufacturer want to adapt recycled ocean plastic to their production from a holistic point of view. Not only focus on personnel who work inside the factory.

**Ozone depletion:**

In this case, the material input of traditional shipbuilding process has 32.97% less damage of the ozone layer than innovative manufacturing process.

**Particulate matter formation (PM10):**

Extremely small particles (with a size of 10um) include acids, organic chemicals, metals, soil or dust particles from vacuum infusion process increase by 5.57% if compared with direct lamination.

### 4.3.2 Comparison of other categories

**Production waste**

Table 14. Environmental impacts of waste treatment.

| | **Climate change ecosystem** | **Human toxicity** | **Ozone depletion** | **Particulate matter** |
|---|---|---|---|---|
| Direct lamination | $- 2.21509E^{-7}$ | $- 1.87819E^{-6}$ | $4.60685E^{-11}$ | $- 1.01171E^{-7}$ |
| Vacuum infusion | $- 2.08140E^{-7}$ | $- 6.03071E^{-6}$ | $- 5.89570E^{-11}$ | $- 4.97871E^{-7}$ |

While calculating the impacts of manufacturing waste, input flows are selected from category: end-of-life treatment/incineration/energy recycling, which means they are sent to incineration station and finally transformed into recycled energy. From the results, production waste treatment has positive impacts in selected categories except Ozone depletion in Direct lamination.

**Energy consumption**

Table 15. Amount of energy consumption in vacuum infusion and direct lamination process.

| **Electricity consumption (KW*h)** | |
|---|---|
| Vacuum infusion | 450 |
| Direct lamination | / |

Due to the difficulty in data collection, the environmental impact of electricity consumption will be analyzed separately. The consumption of Vacuum infusion is calculated according to the equipment technical information. Values for illumination and universal tools are treated as the same in two production method. In this case, only the different part will be taken into consideration. For better efficiency and clearer comparison, Direct lamination process will be ignored, which does not mean there is no energy consumption in it.

Table 16. Environmental impacts of electricity consumption in vacuum infusion process.

| | **Climate change ecosystem** | **Human toxicity** | **Ozone depletion** | **Particulate matter formation** |
|---|---|---|---|---|
| Vacuum infusion | $1.93565E^{-5}$ | $5.7515E^{-5}$ | $4.24476E^{-9}$ | $1.80672E^{-5}$ |
| Direct lamination | / | / | / | / |

In the case at SSPA, the input energy flow is set as electricity from waste incineration – waste incineration of unspecified plastics in municipal solid waste (at plant, average European waste-to-energy plant, without collection, transport and pre-treatment).

**Human health effect of in-house production**

From previous LCIA results, the indicator Human toxicity represents the potential harm of chemicals released into the environment from manufacturing process from a global view. Here in this section, focus will be put on how workers be influenced from production itself. Personnel may be influenced by manufacturing processes and raw material etc.

Air quality:

In direct lamination process, shipbuilders should always wear masks to protect themselves from bad air condition in house as the solvent is used in lamination. Also, acetone puts a threat on workers' health. Though it has been studied extensively and recognized to have low acute and chronic toxicity, it is highly flammable, which could be dangerous. Moreover, if inhaled, acetone could cause a sore throat or cough and influence the human body in the long term (ChemicalSafetyFacts, 2019).

In the vacuum infusion process, with heat treatment, the manufacturing process is much safer because fully cured epoxy has less influence on human body. During the production, there are less harmful gas leakage due to the vacuumed condition of mold and product.

In both manufacturing processes, while operators are grinding or polishing the laminated parts, the workshop could be dusty.

Ergonomics in production:

When ship builders work with direct lamination method, they need to bend frequently. Repetitive manual laminating work may harm worker's spine. Also, in the assembly phase, some heavy lifting tasks make this work method not ergonomic friendly.

Material's toxicity:

Refer to the technical file of release agent provided by GAZECHIM, combustible / explosive vapor air mixture can be formed in use. High concentration of vapors may irritate eyes and respiratory tract and induce narcotic effects. Also, skin can be degreased if get touched with solvents.

**Production efficiency**

Table 17. Cycle time of two manufacturing methods for one boat including manual work and curing waiting time.

| **Cycle time (hours)** | |
|---|---|
| Vacuum infusion | 231 |
| Direct lamination | 125 |

From Table 17, the cycle time of vacuum infusion process is nearly doubled compared with direct lamination.

### 4.3.3 Top contributive sub-processes in two boatbuilding methods

In each boatbuilding methods, the main manufacturing process was divided into several sub-process according to the product structure and working sequence. As shown in Figure 5&14, a boat can roughly be disassembled into six major components: hull bottom, hull side, gunwale, bulkhead, centerboard case and mast step.

Applying dry build material to each component is so-called sub-process. Also, resin infusion and lamination process will be calculated separately as well as the painting process, which is special in direct lamination process (no painting was required in vacuum infusion in this case). Additionally, mold preparation, secondary bonding and finishing processes are assumed to be the same in the two methods. While importing the life cycle inventory data, raw materials were sorted in group by components. Therefore, OpenLCA was able to calculate and compare the environmental impact scores of each sub-process as well.

**Top three contributors in direct lamination process**

Table 18. Top 3 sub-processes of four environmental impact indicators in direct lamination process.

| Category | Climate change ecosystem | Human toxicity | Ozone depletion | Particulate matter formation |
|---|---|---|---|---|
| NO.1 | Hull bottom | Lamination | Hull bottom | Hull bottom |
| NO.2 | Lamination | Hull bottom | Hull side | Lamination |
| NO.3 | Hull side | Bonding/finishing | Gunwale | Hull side |

**Top three contributors in vacuum infusion process**

Table 19. Top 3 sub-processes of four environmental impact indicators in vacuum infusion process.

| Category | Climate change ecosystem | Human toxicity | Ozone depletion | Particulate matter formation |
|---|---|---|---|---|
| NO.1 | Hull bottom | Infusion | Hull bottom | Hull bottom |
| NO.2 | Infusion | Hull bottom | Gunwale | Infusion |
| NO.3 | Gunwale | Gunwale | Hull side | Gunwale |

By ranking top environmental impact contributors of two boatbuilding processes, core sub-processes were identified and they worth more attention in further optimization analysis. Though for two different methods, two tables are slightly different, but hull bottom, hull side, gunwale and lamination/infusion are four major contributors to the environmental influence. Refers to the life cycle inventory, hull bottom, hull side and gunwale are components which contain a big volume of raw material. Lamination and infusion step should be responsible for the high consumption of resin and the extra plastic consumables.

# 5. DISCUSSION

## 5.1 Improvement analysis of boatbuilding process with ocean plastic

In present calculations, the act of trying to use recycled ocean plastic in boat building resulted in a higher environmental influence in all selected impact categories compared with normal boat production. However, the value of this attempt should not be denied and given up in the future. Differences of environmental impact between two types of boats can be investigated to look for the optimization potentials from three aspects.

### 5.1.1 Optimization of environmental impact

**Reduce the amount of raw material inputs**

In Climate Change Ecosystems, Human Toxicity and Ozone Depletion categories, dry build material input for hull bottom part and the lamination/infusion process plays the most important roles. The key contributive flows of $CO_2$ emission are production of PET foam core, glass fiber roving and epoxy resin. Since all these raw materials are assumed to have the same technical characteristics, the only influencing factor is the amount of usage. However, the increased amount of dry build material is basically unavoidable due to the additional ocean plastic. Moreover, the more ocean plastic to be added, then more dry material is necessary to guarantee the fixed position of ocean plastic particles in the product.

For Particulate Matter Formation, the impact values of hull bottom are similar because the $CO_2$ emission from PET and glass fiber roving production varies little between vacuum infusion and direct lamination. When it comes to lamination/infusion sub-process, epoxy resin still plays a crucial role in direct lamination process. But in vacuum infusion, the production of polyethylene terephthalate fibers really matters. The reason why epoxy resin no longer ranks the top position in vacuum infusion process could be the use of large number of plastic consumables such as vacuum bag and resin transport medium etc.

Different from normal Optimists manufacturing, the industry hasn’t set common regulations for Optimists with recycled material. Therefore, one task for further experimental production is to find out the optimal usage of ocean plastic. An optimal percentage of weight might be able to achieve adding the maximum of ocean plastic but the minimum of raw material increase.

**Improve the waste management**

From the life cycle inventory, boats built through vacuum infusion process has more waste from production than conventional laminated boats. The main reason is the extra use of plastic consumables from vacuum infusion. The other reason is a large amount of resin will be taken away by resin transport mat and inlet tubing. In direct lamination process, no ocean plastic is used, therefore the same amount of ocean plastic was treated as waste.

After treatment in waste incineration station, vacuum infusion process still has higher positive influence on four categories especially in Human Toxicity, Ozone depletion and Particulate

Matter. Therefore, the increase of production waste did not really put more pressure on sustainability. In industry, it should always be a focus that waste from production needs proper treatment to reduce its environmental influence.

Moreover, under the current circumstance, ocean plastic is assumed to be collected and processed for both manufacturing methods. However, in real life, the ocean plastic is more likely to be left in the ocean for years. The harm that floating littering have on global ecosystems and marine mammals could be more serious and unpredictable in the long term.

**Reduce the energy consumption in production**

Generally, illumination and universal tools such as electrical grinder or saw act as energy consumers in both vacuum infusion and direct lamination processes. Vacuum pump and industrial heater were special in SSPA.

Though the input energy was selected from electricity from waste incineration from LCA database, the amount of electricity used by pump and heater still put a huge influence on the environment especially in Climate change and Particulate matter formation.

Vacuum pump needs to be turned on through the whole infusion and curing phase. Higher curing temperature guarantees better heat resistant property of products. From a quality perspective, they cannot be simply removed from production to reduce the environmental impacts. To save the energy, alternative equipment with higher efficiency and better workplace design will be helpful.

### 5.1.2 Optimization of production efficiency

Three main reasons why the boat built at SSPA took much longer time than normal ones are longer preparation time, heating time and the sequential workflow.

**Reduce the preparation time of vacuum infusion**

Compared to the traditional manual work, there are much more preparation works need to be done before applying resin in vacuum infusion process according to the operation procedure shown in previous chapter. For instance, the installation of spiral tubing and vacuum bag could be relatively time-consuming even it was done by a professional shipbuilder. In the long term, the preparation time could be reduced by proper training and better organized time schedule.

**Manage the heating and resin curing time**

In normal boat building process, Optimists can be cured at room temperature. At SSPA, Optimists are cured at 50 degrees for more than 36 hours. Longer cure time makes the resin become thinner and permeate the fibers better. Higher cure temperature also increases the heat distortion temperature of boat, which means the products have better heat resistant property. For health factors, it is also safer to work or play with epoxy product that is fully cured.

**Better work schedule design in vacuum infusion process**

The SSPA boats were produced in sequence by components, which resulted in longer manual work time. While in traditional boat building line, different parts are laminated simultaneously at stations. By changing sequential tasks to working parallelly by group, the efficiency of production can be improved.

Cycle time of a boat decides the time from order to market, which is quite important from commercial perspective. Under an experimental situation, it is certainly necessary to take cycle time into consideration but with less priority.

### 5.1.3 Keep track of long-term impacts on human body

According to relevant technical files, epoxy resin and other materials may put a threat on the human body in manufacturing process. Some symptoms may show up immediately but some of them can be harmful after a long time period. Therefore, it is essential for employers to track the health condition of employees in the long term. It will be continuous work and can help researcher with further analysis.

### 5.1.4 Optimization from other impact factors

**Consider the pre-treatment of ocean plastic as a part of life cycle**

In this study, the LCA scope is set to be inside the workshop. In fact, ocean plastic travelled a long distance from selected Swedish beaches before entering SSPA. The pre-treatment such as cleaning, sorting and crushing also result in energy consumption, which cannot be ignored from a cradle to grave scope.

**Manage the transportation of ocean plastic, raw material and personnel**

In present situation, supplier of dry building material and consumables is GAZECHIM, a Swedish composites provider. The company locates in Falkenberg, which is around 100km away from Gothenburg.

What is special in this study is the transportation of personnel in SSPA. To build those Optimists for the ocean ecosystem protection project, the operator travelled from New Zealand. The flight between continents actually has large amount of $CO_2$ emission.

**Improve the end of life treatment of Optimists with ocean plastic**

For the first attempt, five Optimists built at SSPA will show up at various yacht clubs around the country and let the public have a chance to see them during this spring and coming summer.

At the end of life cycle, they are likely to be settled down in related marine museums for exhibitions and education.

**Intangible impacts of plastic in marine ecosystem**

In this study, the Optimist from the control group do not contain any ocean plastic. The same amount of ocean plastic is assumed to be sent to the incineration. However, those marine plastics used are more likely to be left in our ocean. The negative impacts they have on ecosystems and marine mammals is very hard and time consuming to evaluate.

**Better control over the composition and quality of ocean plastic**

The composition of marine plastic debris varies in geography and time scale. Different batches of collected plastic rubbish contain different plastic types. Better control over the composition and quality can reduce the variety in reusing ocean plastic in industry.

## 5.2 Source of errors and credibility of the results

### 5.2.1 Life cycle assessment database availability

The ELCD database used in this case has quite long history and some datasets from it are recorded around 2010s, which are more than 10 years old. However, manufacturing industry has been rapidly developed in past decades. Old data without updating may result in uncertainties of the LCA results.

Additionally, in the OpenLCA calculation model, several alternative production flows are used since it is almost impossible to find input flows that are 100% the same as material flows in real production.

In ELCD, elementary flow' environmental impacts are basically divided into three categories: emission to air, emission to soil and emission to water. In this study category emission to air was chosen for calculation. Under the selected emission category, elementary flows were measured according to population density. To avoid deviation, datasets in unspecified population density group were used in this study.

### 5.2.2 Life cycle inventory data availability

In this study, production data about normal boat building process was based on shipbuilder's experience, assumptions and universal practices.

Due to the lack of real-time data collecting system in process of ocean plastic boat, manufacturing data was not recorded on time.

## 5.3 Lessons of life cycle assessment research

**Extend the scope of LCA**

A cradle-to-grave LCA may be more time-consuming with data collection but it can provide better vision for optimization. Apart from the onsite production, transportation and many other stages should also be included to get holistic analysis.

**Find a better data source for control group**

As the control group in this study, the data quality of the conventional method really matters. In further study, the results of comparison could be more accurate by acquiring data from physical traditional production lines.

**Introduce simulation tools**

The long lead time of data collection always results in low efficiency. To save time, the real time production data collection system will be a key element. Moreover, production simulation can be introduced to the optimization to reduce the workload and resource consumption of research.

## 5.4 Suggestions for reusing ocean plastic in industry

**Raw material inventory control**

Based on this study, the raw material input increased as the recycled plastic was built into the process. Therefore, too much recycled plastic will load higher environmental impact. By building a calculation model of manufacturing process with different amount of ocean plastic as a variable, an optimal amount can be found out where a maximum of recycled plastic can be added to the original process and result in the lowest additional consumable consumptions at the same time.

**Waste management**

The waste of raw material and consumable is unavoidable especially in newly developed manufacturing process with recycled plastic. By introducing the internal recycling inside of the production system, the waste can be reduced.

**Energy consumption**

While reusing recycled plastic in manufacturing, pre-treatment procedure and energy consuming equipment could result in high energy consumption. To reduce the energy usage, this factor should be taken into consideration at the manufacturing processes design stage including equipment selection. Moreover, the source of energy should be as clean as possible. For example, electricity from solar or hydropower has less environmental impact than fossil fuel.

**Cycle time reduction**

While introducing recycled plastic to mass production, the production efficiency and productivity would be important parameters. Emergent production technologies such as industrial robotic can support an effective production system. What’s more, advanced production system design can be helpful to reduce the cycle time in sequence.

**Other factors**

In a comprehensive product lifecycle, many factors that outside of the factory need to be considered as well.

For instance, the transport of material and personnel play significant roles in greenhouse emissions. Therefore, decisions such as the selection of suppliers and location of manufacturing site should be a part of initial evaluation of future applications with recycled plastic.

# 6. CONCLUSION

Optimists built at SSPA between 2018 and 2019 were just a beginning of the journey. From the LCA results and discussion in this study, it is no doubt that there are huge potentials to improve current manufacturing processes with ocean plastic.

The first key to reduce the environmental impacts of Optimists with ocean plastic is modifying the strategy from several points include raw material input, waste management, energy saving and production efficiency. Different from conventional boatbuilding method, the industry hasn't set any common regulations for products with ocean plastic. It is relatively flexible for researchers to modify the reusing strategies. Trade-offs are unavoidable, but it is always optimistic to find an optimal point.

Secondly, always make green decisions on building the value chain. Work with green supplier, reduce the distance of transportation and always choose sustainable energy. In mass production, the loss of sustainability could be eliminated by good work design and schedule.

In summary, even from current results, the manufacturing process of Optimists with ocean plastic hasn't been proved to be more eco-friendly than conventional ones, it is still worth for us to make efforts to adapting recycled plastic into production due to the high potentials in optimization. Optimists för Havet also has a plan to start the new round boatbuilding in the future. By following instructions from this study, pitfalls could be avoided in similar cases. The more applications of recycled material and assessments of the life cycle researcher conduct, the better performance people will get the next time. The reusing of recycled material would be a key to the establishment of circular production.

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# APPENDIX

## A – Input material inventory for vacuum infusion process

| | Category | Amount / unit (g) |
|---|---|---|
| Hull bottom part | Glass fiber roving – 300 | 2700 |
| | Surface mat – 80 | 288 |
| | PET foam core – 1000 | 1800 |
| | Ocean plastic | 960 |
| Hull side part | Glass fiber roving – 300 | 2400 |
| | Surface mat – 80 | 160 |
| | Spray glue | 50 |
| | Ocean plastic | 510 |
| Gunwale | Chopped strand mat glass fiber – 300 | 660 |
| | Glass fiber roving – 300 | 2400 |
| | PET foam core – 1000 | 250 |
| | Ocean plastic | 660 |
| Bulkhead | Glass fiber roving – 300 | 450 |
| | Surface mat – 80 | 24 |
| | Ocean plastic | 95 |
| Centerboard case | Glass fiber roving – 300 | 480 |
| | Ocean plastic | 96 |
| Mast step | Glass fiber roving – 300 | 12 |
| | PET foam core - 1000 | 10 |
| | Ocean plastic | 5 |
| Mold preparation | Wax | 30 |
| | Release agent | 3200 |
| Secondary bonding and finishing | Bonding glue | 1500 |
| Infusion | Vacuum bag | 1940 |
| | Spiral tubing | 523 |
| | Sealant tape | 425 |
| | Epoxy resin | 23475 |
| | Resin transport mat | 850 |
| | Peel ply | 255 |

### B – Energy consumption calculation for vacuum infusion process

| | Working hour | Power | Energy consumption |
|---|---|---|---|
| Vacuum pump | 100hours | 0.9KW | 90KW*h |
| Industrial heater | 180hours | 2.0KW | 360KW*h |

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### C – Input material inventory for direct lamination process

| | Category | Amount/g |
|---|---|---|
| Hull bottom part | Glass fiber mat - 300 | 1620 |
| | Glass fiber mat - 450 | 1620 |
| | PET foam core 13/60 | 1800 |
| Hull side part | Glass fiber mat - 300 | 600 |
| | Glass fiber mat - 450 | 1800 |
| | Woven cloth - 280 | 560 |
| Gunwale | Glass fiber roving – 450 | 1080 |
| | Woven cloth - 300 | 165 |
| Bulkhead | Glass fiber roving - 300 | 90 |
| | Glass fiber roving - 450 | 270 |
| Centerboard case | Glass fiber roving - 300 | 120 |
| | Glass fiber roving - 450 | 720 |
| Mast step | Glass fiber roving – 300 | 9 |
| | Glass fiber roving - 450 | 4.5 |
| | PET foam core - 1000 | 10 |
| Mold preparation | Release agent | 3760 |
| Secondary bonding and finishing | Bonding glue | 1500 |
| Lamination | Epoxy resin | 20937 |
| | Lamination solvents | 3160 |
| Painting | Painting coat | 500 |