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Environmental Impact Assessment of Boatbuilding Process with Ocean Plastic☆,☆☆

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A R T I C L E   I N F O

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A B S T R A C T

Ocean ecosystems are suffering from plastic pollution. To prevent further damage, the 3Rs approach suggests reducing, reusing, and recycling waste. Current solutions include developing waste management systems, public awareness, and waste collection projects to reduce and recycle. However, reuse of reclaimed plastic is limited. This study is as part of an ocean-cleaning campaign. The manufacturing process to produce optimists using ocean plastic was evaluated and compared with conventional boat building as baseline. The environmental impact is higher than the baseline due to more material- and energy-intensive processes. However, adapting processes and integrating recycled materials is necessary for more sustainable and circular production systems.

Introduction

Ocean plastic pollution

Every year, 5-13 million tons of plastic debris end up in the ocean globally (Håll Sverige Rent, 2019). Tons of plastic floating in the ocean unfortunately threaten animals live in the ocean. Entanglement, ingestion and chemical contamination are three main risks cause by plastic debris (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).

Studies have calculated 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 (Cordier and 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 which are full of ocean debris in Kosterhavet national park, government need to spend more than 1 million SEK each year (Håll Sverige Rent, 2019).

Current applications of ocean plastic in industry

While the whole society are putting more efforts into reducing and recycling ocean plastic, the industry is working on reusing it as well. Presently, processed plastic debris from ocean is gradually adapted in some packaging and textile production.

However, there are barriers and gaps between proposals and reality. High financial investment and complex pre-treatment of ocean plastic put pressure on those pioneers. Also, the lack of universal standards or regulatory policies makes the industry confused sometimes. For instance, different projects aim at their own quality and safety requirement (Caliendo, 2018).

Boatbuilding project at SSPA

In Sweden, a campaign *Optimists för Havet* was launched in 2018. Public was organized to clean selected beaches and the plastic rubbish they collected were processed to explore possibilities in reusing. According the project manager, during the year of 2018, the campaign held 10 clean-up-events and in total around 9 cubic meters of plastic debris was collected. Afterwards, 6.5 cubic meters containing hard plastics was sent to Envir, a company which is specialized in waste composition analysis. Envir had the mission to sanitize and sort the plastics into different types (PPE, PET and so on). Then those cleaned plastic was sent to Chalmers material science lab to be hardened for later production. The manufacturing processes were at SSPA, a Swedish shipbuilder. In their workshop, five optimists were built with ocean plastic fragments.

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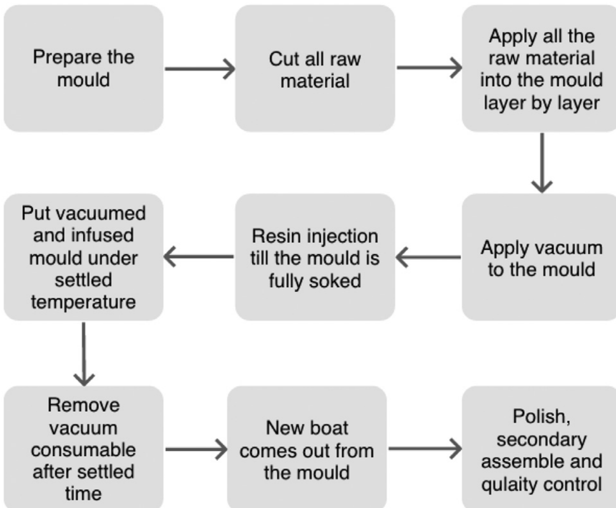

Fig. 1. General manufacturing sequence of VI process.

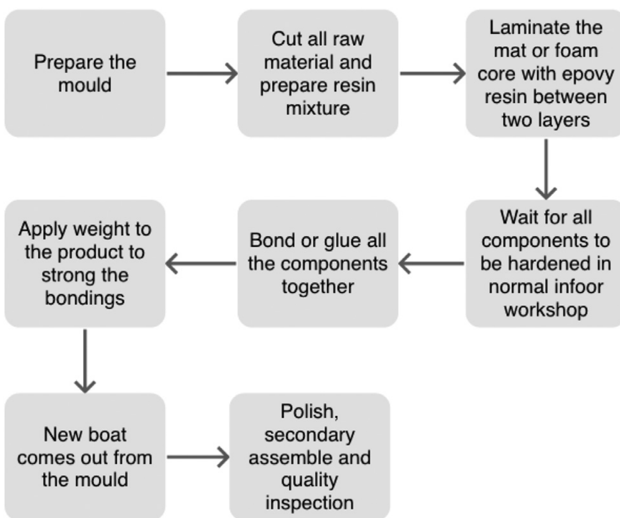

Fig. 2. General manufacturing sequence of DL process.

Two boatbuilding methods for optimists

Vacuum infusion uses the vacuum pressure to drive resin into a laminate. As shown in Fig. 1, 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 (Glast, 2019).

Due to the use of ground ocean plastic in production, traditional direct lamination cannot properly keep the fragment uniformly distributed around the boat body.

The baseline used for the study is a boat built in direct lamination. The general manufacturing sequence is shown in the Fig. 2. Conventionally, this shipbuilding process is done by ship builders manually under normal indoor temperature and without special accessorial equipment except universal tools. In a typical hand layup process, reinforcements are laid into the mold and manually wet out using brushes, rollers etc.

The most significant difference between vacuum infusion and direct lamination is that in vacuum infusion epoxy resin will be applied in the end of whole process under the work of vacuum pump and heater except the pre-made part with ocean plastic for hull side (Compositeinteg1, 2013).

Research questions and aim

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

a) How would the reusing of ocean plastic influences the environmental impacts of manufacturing processes?
b) How to strengthen the value of reusing ocean plastic or eliminate the limitation?

To answer the research questions, this study will evaluate and analysis the environmental impacts of building a boat with ocean plastic compared to a baseline without ocean plastic.

Methodology

Life cycle assessment method

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 (Chen and Huang, 2019). The scope of the LCA in this paper was defined as the manufacturing processes from the arrival of raw material to the finishing of the boat. The function unit of environmental impact calculation is a hull body of optimist.

Open LCA 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.

Based on the open source platform, the choice of databases and impact methods is flexible. Usually an LCA database/set is organized by third-party organizations. Database/set contains a huge collection of elementary life cycle data. Impact assessment methods are used together with databases in the models built on the OpenLCA platform. The method identifies the calculation equations between every single input and corresponding impacts. In this study, ELCD (European reference Life Cycle Database) was selected as the database for the secondary data relating to material and energy flows. ReCiPe was used as the impact method.

Selection of life cycle impact categories

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

Table 1
Primary data and information sources.

Optimists för Havet	Plastic collection and treatment
Chalmers material lab	Data and information about pre-treatment
SSPA	Production data from
Suppliers	Technical data and files of raw material
Others	International regulations etc.

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 the air. PM is measured in PM10 equivalents, which means particles of a size of 10um.

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

Data collection

As shown in the Table 1, production data of detailed manufacturing processes was collected from SSPA. Information about raw material and ocean plastic fragment are from suppliers and Chalmers material science lab.

For the boat without ocean plastic, data was collected from document as well as production data from experienced ship builders.

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.

Life cycle impact calculation model

Together with data from above life cycle inventory, the life cycle impact can be calculated by following the model shown in Fig. 3.

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 flow.

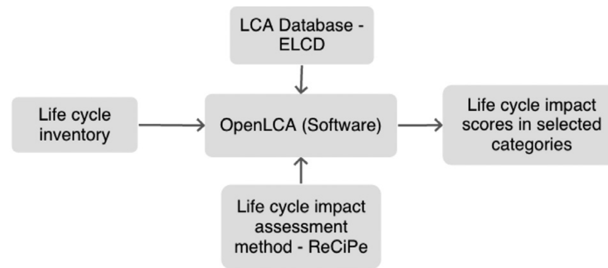

Fig. 3. Calculation model of life cycle impact in selected categories.

Results

Environmental impacts of manufacturing processes

For each boat, the CO_2 emission of production with ocean plastic and VI process increases by 23.51% compared to DL shipbuilding without ocean plastic.

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

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

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

Environmental impacts of production waste

In the calculation of the impacts from waste management, the 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 DL. See the values shown in the Table 3.

Energy consumption and production efficiency

The electricity consumption of production is calculated according to the equipment technical data. Values for illumination and universal tools are treated as the same in two production methods. In this case, only the different part will be taken into consideration. For better efficiency and clearer comparison, electricity used in DL process was ignored, which does not mean there was no energy consumption in it.

When it comes to the production efficiency, from Table 4, the cycle time of VI is nearly doubled compared to DL.

Table 2
Environmental impacts of manufacturing processes.

	Climate change	Human toxicity	Ozone depletion	Particle matter formation
DL	7.35E-7	9.94E-5	4.77E-9	1.25E-5
VI	9.07E-7	1.21E-4	6.34E-9	1.32E-5
Difference	1.72E-7	2.13E-5	1.57E-9	0.70E-5
(%)	23.51% ↑	21.51% ↑	32.97% ↑	5.57% ↑

Units: Kg CO_2 / 1.4-dichlorobenzene/kg CFC-11/PM10

Table 3
Environmental impacts of production waste.

	Climate change	Human toxicity	Ozone depletion	Particle matter formation
DL	-2.22E-7	-1.88E-6	4.61E-11	-1.01E-7
VI	-2.08E-7	-6.03E-6	-5.90E-11	-4.98E-7

Units: Kg CO_2 / 1.4-dichlorobenzene/ kg CFC-11/ PM10.

Table 4
Electricity consumption and cycle time.

	Electricity consumption	Cycle time
DL	/	125 hours
VI	450 kW*h	231 hours

Discussion

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 a 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 increases.

Improve the waste management

From the life cycle inventory, boats built through vacuum infusion process have 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 has 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.

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.

Optimization of production efficiency

There are 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 a 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.

Optimization from other impact factors

Consider the pre-treatment of ocean plastic

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

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.

Consider the intangible impacts of ocean plastic

In this study, the optimist from the control group did 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.

Control over the ocean plastic composition and quality

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.

Source of errors and credibility of the results

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.

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 the process of ocean plastic boat, manufacturing data was not recorded on time.

Lessons of life cycle assessment case study

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.

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 includes 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. *Optimist 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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