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Spoilt - Ocean Cleanup: Alternative logistics chains to accommodate plastic waste recycling: An economic evaluation

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ABSTRACT

Every year about 300 million tons of plastic is produced, resulting in more than five trillion plastic particles currently floating in the oceans five largest convergence zones. The Ocean Cleanup is testing a method to passively collect this floating plastic debris, transport, recycle, process and sell it. The purpose of this paper is to evaluate alternative logistics chains to accommodate ocean plastic waste recycling by connecting transport with data collection and data analytics. The scenarios are based on different geographical destinations, supply chain lengths and types, and offered local development opportunities. A new reverse logistics channel dedicated to the Ocean Cleanup is developed, as existing reverse logistics supply chains are not able to capture the specifics of the plastic waste collection.
Performances of the different scenarios are assessed by collecting data (on plastic volumes collected from the Ocean, on usage of plastics as a resource, and on transport cost) and usage of a detailed integrated model which enables a performance comparison of different logistical structures on logistics costs and on plastics production outputs. The cheapest and most disappointing solution would be to do nothing. However, the analysis shows that more complicated logistic structures whereby the collected plastic waste is used to produce glasses, socks, and carpets can lead to sustainable business models for cleaning up the Oceans. If the focus would be only on cost, the best model would be to minimize the transport distance and focus on San Francisco as closest port for the selected gyre to be analyzed.

1. Introduction

Every year about 300 million tons of plastic is produced, of which a portion enters rivers and oceans (Boucher and Friot, 2017). Plastics that float in seawater can be cast ashore through currents and winds, or they will accumulate in so-called convergence zones (van der Zwet et al., 2017). Plastic in the oceans comes at various degrees of deterioration (due to breakdown of plastics into microbes) making cleaning the oceans in full a challenging task. A part of the collected ocean plastics might be difficult to re-use due to this deterioration. The five largest convergence zones, called gyres, are in the subtropical areas (South and North Pacific, South and North Atlantic, and the Indian Ocean) (Cozar et al., 2014). It is estimated that a minimum of 5.25 trillion plastic particles float in these five zones, weighing over 268,000 tons (Eriksen et al., 2014). In recent years, many ideas are pitched on how to clean the oceans. It can be argued that The Ocean Cleanup is the most well-known and developed idea that is currently being worked on. The Ocean Cleanup is an environmental engineering company dedicated to tackling the world's ocean plastic problem and will figure as our example throughout this paper. To accumulate these plastics, the Ocean Cleanup is developing a complex system of sensors, platforms and ocean vessels that operates continuously. The Ocean Cleanup is developing a drifting array that passively catches floating debris, by moving slower than the current.

In a paper written by Pasternak et al. (2018), they discussed the transport mechanisms of floating marine debris to and from the Israeli coast and towards the collection area for floating debris (the Levant Basin in the eastern Mediterranean). In our paper, the transport mechanisms towards the collection areas (gyres) are assumed and instead we focus on the collection and further processing of the plastics from the oceans. To do so, the Ocean Cleanup Systems (OCS) will be placed in the ocean and an anchor slows down the movement of the system so that the speed of the current is faster than the speed of the system (this 'traps' the plastic in the OCS). The shape of the system enables the plastic to move towards the center, where a processing platform is situated that collects and stores the plastic. The plastic waste collection rate is estimated to be 65 m^3/day (Slat and et al., 2014). Given the estimated size of the processing platform, this would mean plastic needs to be picked up by a ship every 45 days. Once the OCS is emptied, the plastic waste needs to be transported to the mainland. Due to the large distances between the gyres and the mainland, this needs to be done efficiently. Onboard ships, plastics could be stored unprocessed between the pickup and drop-off points. After unloading in the port,

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the plastic waste could be transported to a recycling factory where it will be processed, recycled and sold, made into products or incinerated. However, there is also the possibility to start with the processes of separating and recycling the plastic waste onboard the ships, while being transported towards the mainland. Both plastic recycling, processing onboard and on the mainland have advantages and disadvantages. In this paper, we develop a bi-objective reverse logistics channel seeking to optimize ocean waste collection and processing while maintaining cost minimization. This paper aims at interdisciplinary analyzing the optimum ocean plastics recycling solution from a technical, transport and logistics, and cost-and-benefits point of view. The main research question in this paper is: How to efficiently and sustainably transport, process, and sell plastics collected from the oceans?

The remainder of the paper is divided into four sections. Section 2 discusses the geographical boundaries of the system and the different possible logistics structures for processing ocean plastic waste. Section 3 gives theoretical and modeling backgrounds of reverse logistics models and cost models and integrates these into the interdisciplinary approach of technology, transport and logistics and cost and benefits to analyze ocean plastics collection and recycling. Section 4 discusses the developed cost model and presents the results of the different possible solutions and also discusses the sensitivities of the respective scenarios. Section 5 discusses the conclusions of this paper and indicates further research.

2. Possible logistics structures to clean up the oceans

2.1. The geographical boundary of the Ocean Cleanup Systems

When it comes to cleaning the oceans, the design goal is to minimize the impact on the environment throughout the entire process of collecting, transporting, processing and possibly selling recycled plastics. This entails, for example, avoiding bycatch of marine life, minimizing the carbon footprint of the constructions and minimizing the carbon footprint of the supply chain processes (Slat and et al., 2014). In this respect, a study performed by Xifeng et al. (2013) shows that it might be desirable to have more facilities or port locations than economically optimal to reduce the carbon dioxide emissions (Xifeng et al., 2013). If there are more facilities or ports, the average transport distances might be lower (leading to better environmental performance) because the locations are closer but costs can increase due to the need for more locations. According to Di Maria and Micale (2013), the collection vehicle compaction ratio, waste density, and vehicle load capacity utilization can significantly affect the total collection costs. These points have been taken into account when designing the scenarios as discussed later on. Each of those scenarios is linked to a specific geographical location in the world.

The North Pacific Subtropical Gyre is the largest gyre holding plastic waste in the oceans. For this reason, Ocean Cleanup operations start in this gyre and will use the relatively close Port of San Francisco as its primary port (Slat and et al., 2014) (see Fig. 1). Sorting the collected ocean waste is a difficult process, due to its complex composition and, therefore, the Port of Esbjerg in Denmark presents a strategic second location to ship the collected ocean waste to, as it situates a potential partner of the Ocean Cleanup that could assist in sorting through the complex mix of ocean plastic waste (van Engelshoven, 2017).

A study by Godfrey (2019) on the many challenges of plastic waste in developing countries suggests that improving local waste collection provides opportunities in terms of building recycling and recovery economies and thus creating labor and growth (Godfrey, 2019). Based on this, outsourcing the sorting, recycling, and reproduction of ocean waste plastics to developing countries can create local and sustainable development of the area around the port, if done responsibly and with respect to the people (labor conditions, public health) and the environment. However, several developing countries, such as China, recently banned the import of plastic waste from developed countries (Los Angeles Times, 2019), mainly to stop the smuggling of non-recyclable waste. Though the Indonesian government also put a ban on importing mixed undocumented waste, they have been collaborating with the Ocean Cleanup on preventing plastic waste from one of the world's most polluted rivers (in Jakarta) to enter the oceans. For this reason, the Port of Tanjung Priok, on the island of Jakarta, Indonesia has been selected as the third geographical location in this paper. The Port of Tanjung Priok is Indonesia's busiest and most advanced port and is continuously expanding.

2.1.1. An important cost driver: shipping distances

The geographical locations included in the analysis in this paper are shown in Fig. 1, along with their potential shipping routes. The collection site that has been selected within the North Pacific Subtropical Gyre is commonly referred to as the Great Pacific Garbage Patch (GPGP) and is described as a ‘Gyre within a Gyre’ (Howell et al., 2012). In this GPGP the highest concentrations of plastics can be found (Eriksen et al., 2014) and the center of the GPGP can be found at a distance of roughly 2000 km from the port of San Francisco. The distances from this collection site towards the port of Tanjung Priok and Esbjerg are roughly 12,500 and 17,000 km respectively. Shipping distances are approximated using online nautical distance calculators and form an important cost driver in the transport and logistics cost and therefore part of the bi-objective research problem is to aim for cost minimization (SeaRoutes, 2019).

2.2. Composition and recycling of ocean waste

It is expected that the quantity of ocean waste collection is roughly 7000 tons annually (Slat and et al., 2014). In an interview with a former employee of the Ocean Cleanup, it has come forward that around 52% of the ocean waste consists of ghost nets, while 47% of the waste is rigid plastics. Ghost nets can be further divided between fishnets and ropes, whereas rigid plastics can be divided between black and non-black plastics (van Engelshoven, 2017). This division of the expected collected plastic waste is shown in Fig. 2. It is important to acknowledge that plastic in the oceans comes at various degree of deterioration (breakdown into microbes) making collection and reuse a challenging task. The business case of recycling these ocean plastics depends on the collection costs, transport and logistics costs, the costs of aborting and re-use and the part of the ocean plastics that can be reused. The actual dynamics of plastic recycling, especially in terms of costs, potential uses, origin and alternative solutions to reduce plastic in the oceans is outside the scope of this paper but can certainly lead to further research once a feasible transport and logistics model has been chosen.

In traditional plastic recycling, the process consists of five stages. However, the current generation of separating and recycling machines cannot separate the complex composition of different materials and sizes of the collected ocean waste. For this reason, a traditional separation and recycling process cannot be applied to ocean plastic waste. The initial separation of the rigid plastics and ghost nets need to be done by manual labor. In this step, the ghost nets could already be further separated in fishing nets and ropes. The rigid plastics that will remain could then be processed and recycled according to a traditional five-stage method. This process is visualized in Fig. 3.

2.3. Transportation logistics structures and scenarios

In general, statistical methods, operational research methods or simulation are preferred over case study research. However, in the case of the Ocean Cleanup, there is not a large database that covers logistics costs, production and storage costs, operational characteristics, and in-depth ocean plastics characteristics. Therefore, in this research, case study analysis is a viable option also because experiments and surveys are not serious options in this stage of the Ocean Cleanup Project. Case studies are the preferred approach when ‘why’ or ‘how’ questions are used, when the focus is on a contemporary phenomenon within some real-life context (such as the Ocean Cleanup), and when the investigator has little control over events. Some potential disadvantages of case studies are (Yin, 2017): a lack of rigor in case studies, lack of basis for scientific generalization, and sometimes long-lasting research efforts.

Fig. 1. Core geographical locations that are important to the Ocean Cleanup.
Source: Adapted from http://lakodosajta.info/unlabeled-world-map.html/printable-blank-world-outline-maps-royalty-free-globe-earth-and-unlabeled-map.

Designing the logistics structure of plastic waste recycling via a more traditional path would mean the plastic waste is collected at a certain point, after which it is transported towards a sorting center or factory for further processing. Since the ocean plastic waste has no purchase costs (other than collection from the oceans), the waste can either be transported towards a storage location (and potentially incinerated) or sorted and transported towards a production location, where products could be made of certain categories of the recycled ocean plastic waste. This focus on cost minimization would be a traditional economic method which we will refer to as the cost minimization case (scenario 1) and is linked to the Port of San Francisco as it situates closest to the GPGP, thereby minimizing the transport distance and thus costs.

An alternative method would be to seek a more balanced approach where next to cost minimization also social and environmental impact is important. When we refer to the environmental impact of the OCS in this paper we refer to optimizing the logistics chain of the OCS and to the degree to how much of the collected ocean waste is being recycled into new products. We will refer to this as the 'Balancing costs and social impacts scenario', or simply as scenario 2. It balances costs and social impacts in the sense that the focus is on minimizing costs while also recycling part of the collected waste into new products and creating local revenue. As the Port of Esbjerg situates a potential partner to handle part of the collected waste, it makes sense to transport the collected waste directly to this part for recycling, hence scenario 2 is linked to the Port of Esbjerg (also other

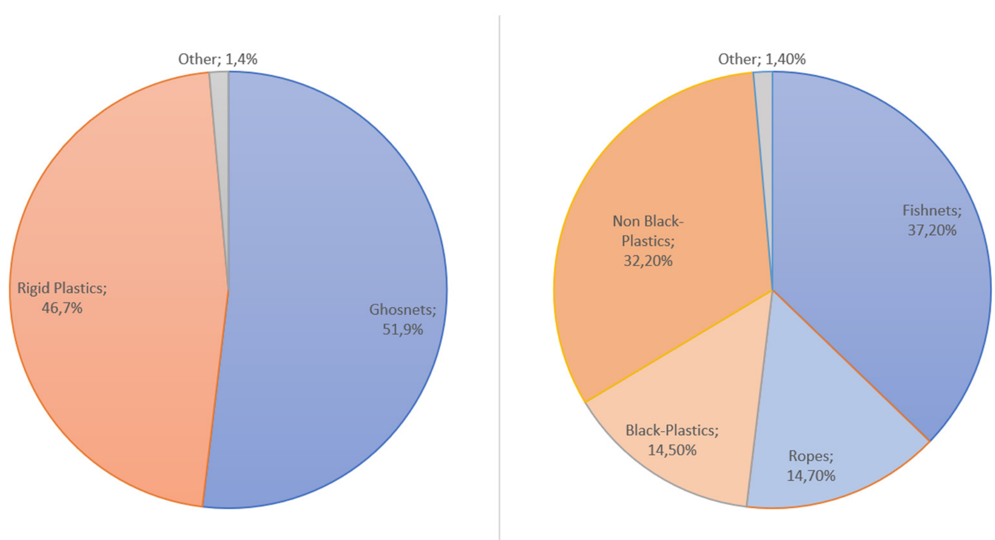

Fig. 2. Composition of collected ocean waste. Left; general composition of rigid plastics versus ghost nets. Right; detailed composition.
Source: van Engelshoven (2017).

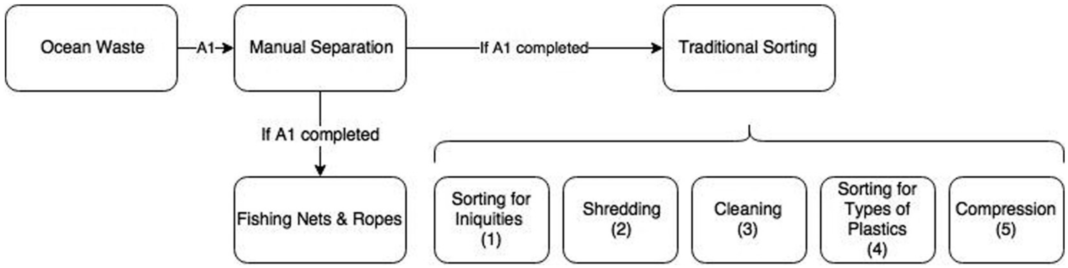

Fig. 3. Overview of plastic waste recycling in the case of the Ocean Cleanup combined with the five-stage approach of traditional plastic waste recycling.
Source: Five-stage approach adopted from Hopewell et al. (2009).

ports with companies that process plastic waste could serve as example port). In this scenario, the much higher transport costs must be compensated by benefit generating activities otherwise this scenario is not feasible.

The design of logistics networks is increasingly changing from a pure cost minimization perspective towards a more balanced perspective that minimizes the environmental impact and at the same time maximizes the social impacts. As mentioned in Section 1. the Port of Tanjung Priok in Indonesia has been selected as a geographical location as it shows opportunities in terms of building recycling and recovery economies and thus creating a positive social impact. This scenario is referred to as the '100% social impact scenario', or simply scenario 3. The focus in this scenario is on social benefits and seeks maximization of the use of relatively cheap labor in developing countries to generate economic activities (benefits) and at the same time making up for the higher transport costs to reach this destination.

In scenarios 2 and 3, the sorting process of the ocean waste could be done onboard of the transportation product tanker vessels. After arriving at the port, the sorted materials can then be used as raw materials to produce high-end glasses (The Independent, 2017) (from the plastics) and, for example, socks (Steele, 2017; Morgan, 2018) and carpets (from nylon ropes and fishing nets) (Plastics Make it Possible, 2018; Polychem USA, 2018). Altogether this results in three assumed scenarios for the transportation, sorting, and further processing of ocean plastic waste as depicted in Table 1 below. Per scenario, the variables that apply to the transport supply chain solution are depicted with an 'X'.

2.3.1. Scenario 1; San Francisco cost minimization

In the cost minimization scenario, ocean waste is collected by a product tanker and transported to the port of San Francisco. Via the port, the ocean waste is transported to a storage location. Via the port, the collected ocean waste is then transported to an inland location where the waste will be stored until advanced recycling techniques are further developed that does not require time-intensive hand-sorting or until suitable buyers for the waste are found (Fig. 4).

Table 1
Alternative logistics chains to transport, sort, and process ocean plastic waste.

Scenarios/variables	1. Costs minimization (SF, 2000 km)	2. Costs and social impacts balanced (ES, 17,000 km)	3. 100% social impact (TP, 12,500 km)
Sea transport	X	X	X
Port handling	X	X	X
Hinterland transport	X	X	X
Storage	X	X	
Recycling		X	X
Production		X	X

SF = Port of San Francisco, United States; ES = Port of Esbjerg, Denmark; TP = Port of Tanjung Priok, Indonesia.

2.3.2. Scenario 2; Esbjerg balancing costs and social impacts

In this case, besides cost minimization also social impacts are important. The plastic waste is transported by the product tanker directly to the Port of Esbjerg, Denmark. Sorting of the ocean waste takes place on the ship (hand-sorting only). The sorting divides the ocean waste into three categories: fishnets, ropes, and plastics. Sorting could take place in a 24-hour operation schedule. After arrival in the port of Esbjerg, the sorted fishnets and ropes are transported to a storage location, while the plastics are transported to a glasses production location (see Fig. 5).

2.3.3. Scenario 3; Tanjung Priok 100% social impact

In this case, the focus is on maximizing social impacts. The plastic waste is transported by the product tanker directly to the Port of Tanjung Priok, Jakarta, Indonesia. This is Indonesia's busiest and most advanced port and is continuously expanding. Outsourcing the sorting, recycling, and production of ocean waste plastics to developing countries can create local and sustainable development of the area around the port if done responsibly and with respect to the people and the environment. For this reason, this scenario focusses on creating a 100% social impact. Sorting of the plastics waste takes place on the ship (hand sorting only). The sorting divides the plastic waste into three categories: fishnets, ropes, and plastics. The sorting takes place in a 24-hour operation schedule, meaning 3 shifts of 8 h. After arrival in the port of Tanjung Priok, Jakarta, there is no transport to storage locations but it is assumed that all four categories of collected waste are re-used. The nylon fishnets and ropes are re-made into socks and carpets. Black plastics are sold and non-black plastics are recycled into glasses and sold. Especially the last two scenarios built upon the idea also expressed by Meira de Sousa Dutra et al. (2018), whereby waste collection and sorting can serve as raw materials again and result in additional created employment besides the initial financial profit-seeking (see also Fig. 6).

3. Reverse logistics: theories and models to clean up the oceans

3.1. Theory on logistics network structures

3.1.1. Traditional and sustainable logistics networks

In traditional logistical structures, strategic (e.g. location of factories), tactical (e.g. the destination of products end-of-life) and operational (e.g. the choice of suppliers, third parties, etc.) decisions are made (Quariguasi et al., 2008). These decisions are made in an integrated way to streamline the flow of raw materials, intermediate products, and end-products via production locations, and storage locations towards the end consumer using distribution. According to Fleischmann (2001), "The location of production facilities, storage concepts, and transportation strategies are major determinants of supply chain performance". The design of logistics networks is increasingly changing from a traditional pure cost minimization perspective towards a more balanced perspective that minimizes the environmental and cost impact and at the same time maximizes the social impacts. Literature into logistics network design is mostly divided into two approaches: minimizing cost or minimizing environmental impact (Bloemhof-Ruwaard et al., 2004).

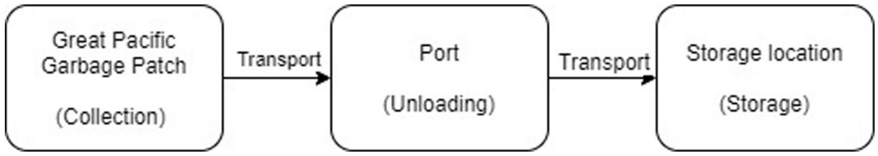

Fig. 4. Model for cost minimization case.

The main activities influencing costs and environmental impacts in logistics networks are transportation, manufacturing, product use, and end-of-use alternatives. Especially these end-of-use alternatives are receiving more and more attention via reverse logistics.

3.1.2. Reverse logistics networks

Researchers agree that the macro drivers for sustainable development (economic, environmental and social drivers) are the same for designing and implementing a reverse supply chain (Seitz, 2006; De Brito, 2004; Rogers and Tibben-Limbke, 1998). However, reverse distribution networks are not necessarily the symmetric picture of forward distribution. Most of them have a "many-to-few" (convergent) network structure instead of a "few-to-many" (divergent) structure (Fleischmann et al., 1997). According to Rubio et al. (2008), research on the strategic aspects of reverse logistics is scarce. Das and Chowdhury (2012) offered a recycling logistics model for various electronic product wastes to minimize the overall processing costs. Their model consisted of four recycling phases: collection, separation, recycling, and repair. The final site included a dumping point, primary market, and a secondary market. They found that transportation costs constitute a major part of recycling costs. Therefore, they concluded that the reduction of transportation costs is the best way to reduce the overall costs of the system. In our paper, especially the strategic level takes center stage as we compare and evaluate alternative logistics chains for cleaning up the oceans from plastics. In general, plastics for recycling can be collected via a network of various methods, separation centers, sorting centers, and reprocessors (Bing et al., 2014). In our case, the plastics failed to be collected for end-of-use alternatives such as re-use, refurbishing, recycling, or energy production but instead ended up in the oceans.

3.1.3. Characteristics of a reverse logistics supply chain

Terrance et al. (1992) suggest that a reverse logistics channel (RLC) can take different forms according to the function and capacity of the reverse logistics activities network. These different forms influence the cost and environmental impact of the respective supply chains (Terrance et al., 1992). For example, carrying out sorting activities on the collected plastic waste from the oceans on-board the ship may help to minimize costs by making transport time productive. Overall, the RLC consists of a generic logistics network and a generic treatment process that is tailor-made for the Ocean Cleanup (see Fig. 3). El Korchi and Millet (2011) deconstructed a reversed logistics channel in a generic logistics network and a generic treatment process. They deducted that a general logistics network contains the following four elements; customers, grouping centers, central warehouses, and production centers (El Korchi and Millet, 2011). Within the logistics network of the Ocean Cleanup, this network looks somewhat similar, though differences are present. For the generic logistics network, the following changes in the model need to be made: the product (ocean plastic waste) is collected by the oceans current and centered in the natural convergence zones, in contradiction to products that are collected from customers and consolidated in grouping centers. The collection of plastic waste at the processing platform in the OCS can be seen as the 'central warehouse', where the product is being stored. After this, the plastic waste is being transported to a production center. Furthermore, the generic treatment process can be divided into the following steps; product inspection, product sorting, disassembly, cleaning, modules inspection, and module sorting.

3.1.4. Generic treatment process of plastics

The remanufacturing literature (Sundin and Bras, 2005; Amezquita et al., 1995) and our analysis of industrial remanufacturing processes show that waste products, during transfer in the logistics network, can go through the following treatment process: after collection, waste products are inspected for sorting into manufacturable and non-manufacturable products. The manufacturable products are then disassembled and the reusable modules are pre-identified according to durability and lifecycle criteria. They are cleaned, inspected and sorted. This treatment process allows keeping reusable used modules ready for assembly with other new modules to form a remanufactured product.

The generic treatment process for the Ocean Cleanup shows some differences. Ocean waste will be picked up from the oceans no matter what, and thus will not undergo inspection. Next, the products will be sorted in the fishing nets, ropes, black and non-black plastics, and inequities will be removed. Disassembly of the products will not take actively place within the Ocean Cleanup logistics but is more a part of the sorting process due to the specific and difficult composition of the waste. After this, products will be cut into smaller pieces, cleaned, further sorted into batches of specific types of plastics and finally compressed into blocks. The final generic structure of the Ocean Cleanup Reversed Logistics Chain can be seen in Fig. 7.

3.1.5. A reverse logistics network to collect plastics from the oceans

When all options such as re-use, remanufacturing, refurbishing and recycling do not work we come to the situation of the large plastic collections now observable in oceans worldwide. That is where our new logistics model starts when all other plastic waste collection options have failed. We try to maximize the plastic waste collected and minimize the transport, port, storage, and production costs. The moment of when to separate the plastics is an important decision. The new logistics network structure for plastic waste collected from oceans and oriented upon 'few-to-few' distinguishes our work from others. The paper also compares and evaluates different lengths of supply chains that handle plastic waste from oceans.

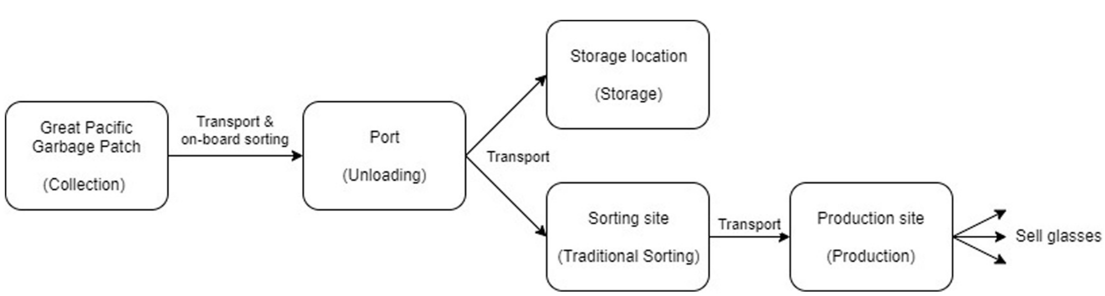

Fig. 5. Model for balancing costs and social impacts.

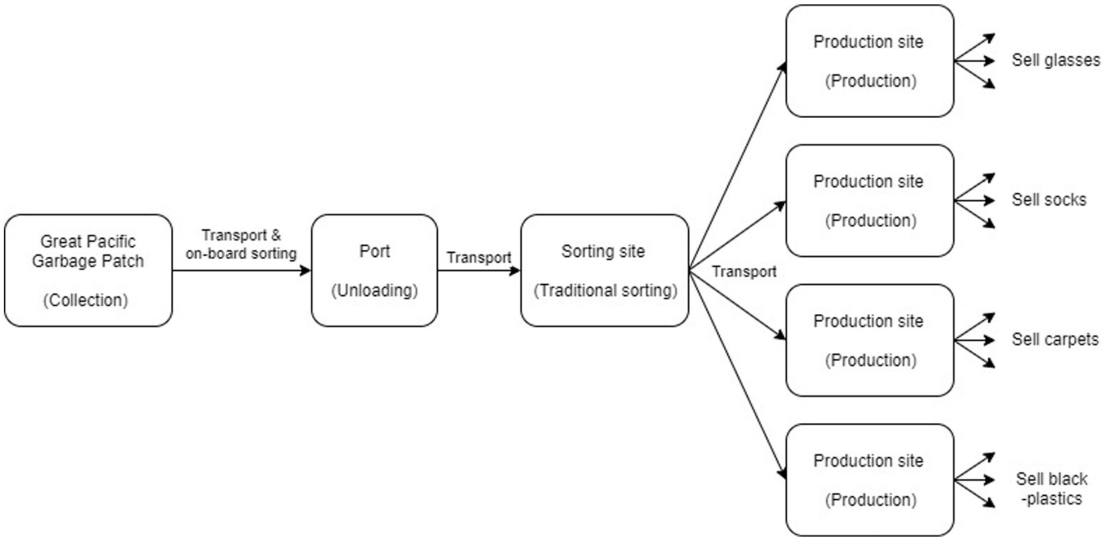

Fig. 6. Model for focus on 100% social impact.

Contrary to normal distribution networks in which products are assembled at the source or during the flow, plastic waste is separated and sorted along with distribution from the sources to the end processors (Bing et al., 2014).

3.2. Modeling reverse logistics for cleaning up the oceans

Reverse logistics for cleaning up the oceans can be modeled in different ways as several methods exist to analyze the respective reverse logistics models on their respective variables. For example, the integer programming problem consists of a mathematical optimization problem where some or all of the variables are restricted to be integers. Often the objective function and the constraints (other than the integer constraints) are linear (therefore; integer linear programming (ILP)). ILP seems less suitable to model the reverse logistics problem as many variables will not be linear due to changing scale efficiencies. Alternatively, a hybrid algorithm combines two or more other algorithms that solve the same problem. This is often implemented to integrate features of each so that the hybrid algorithm is better than its components. Multi-Objective Programming (MOP), is concerned with mathematical optimization problems involving more than one objective function being optimized at the same time. Given the initial sole focus on cost minimization, this approach seems less suitable (given the lack of multiple objectives). A more elaborate review of reverse logistics analyzing methods can be found in Govindan and Soleimani (2016). Given the focus of this paper, the minimum optimization method is developed and applies detailed cost function models for the respective parts of the reverse logistics supply chains for cleaning up the oceans. All cost functions discussed in this paper are annual costs based on a continuous OCS cycle unless otherwise specified. Altogether this forms the core of our interdisciplinary approach to analyze the optimum ocean plastics recycling solution from a technical, transport and logistics, and cost and benefits point of view.

3.2.1. Cost functions scenario 1

The cost minimization base scenario consists of four steps; transportation from the site to the port of San Francisco, port handling, transportation to a storage site and storage of the ocean waste. The cost function of this case can be defined as:

$$Cost = transport\ costs\ from\ GPGP\ to\ SF + port\ handling\ costs + hinterland\ transport\ cost + storage\ cost$$

$$Transport\ cost\ from\ collection\ site\ to\ final\ port = CY * \frac{distance}{v/hours\ per\ day} * F * Pf + C_{sh} + C_{cr} \quad (1)$$

$$where\ CY = \frac{\text{days per year}}{\text{h}}\ and\ \prime distance\prime = d1, d2, or\ d3 \quad (1a)$$

(based on number of cycles per year, shipping time, average shipping speed, fuel consumption, average fuel price, annual ship purchase costs, and crew costs)

$$Port\ handling\ cost\ SF = Q * C_{p_{SF}} \quad (2a)$$

(based on the volume of collected ocean waste and port handling costs)

$$Hinterland\ transport\ cost = W * C_{rt} * d_h \quad (3)$$

(based on the weight of collected ocean waste, hinterland transportation distance, and road transportation costs)

$$Storage\ \ cost_{SF} = C_i * W \quad (4)$$

(based on the weight of collected ocean waste and storage inventory costs).

3.2.2. Cost functions scenario 2

In scenario 2, where part of the collected ocean waste will be recycled into new products, the costs can be divided into two functions. The recycling costs consist of the sorting cost by manual labor onboard and the net-treatment costs of plastic on the mainland. Furthermore, since in this function the plastics will be recycled and used to produce products, the storage cost function is adjusted for the percentage of ghost nets and ropes.

$$Cost = transport\ costs\ from\ GPDP\ to\ Esbjerg + port\ handling\ costs + hinterland\ transport\ costs + storage\ costs + recycling\ costs + production\ costs - Revenues\ of\ sold\ recycled\ products$$

$$Port\ handling\ cost\ Esbjerg = Q * C_{p_{ES}} \quad (2b)$$

(based on the volume of collected ocean waste and port handling costs)

$$Recycling\ costs = Sorting\ cost\ onboard + plastic\ net - treatment\ cost \quad (5)$$

$$Sorting\ cost\ onboard = T_s * CY * C_{dh}, where\ C_{d_h} = \frac{N_w}{3} * C_w, \quad (6a)$$

$$where\ T_S = {}^{d_2/v}\ and\ CY = {}^{365}/_{h} \quad (6c)$$

(based on the number of cycles per year, time of disassembly required, and hourly cost of disassembly)

$$Plastic\ net - treatment\ cost = W * Cnt_p * \alpha_{pl} \tag{7}$$

(based on the weight of collected ocean waste adjusted for plastics share and the net-treatment costs of plastics)

$$Production\ costs\ glasses = C_g * V_g \tag{8}$$

(based on the production costs of recycled glasses and the volume of recycled glasses)

$$Revenues\ glasses = V_g * P_g \tag{9}$$

(based on the volume of recycled glasses and the average price of recycled glasses)

$$Revenues\ black - plastics = P_{bp} * W * \alpha_{bp} \tag{10}$$

(based on the weight of collected ocean waste adjusted for black-plastics share and the raw price of black-plastics).

3.2.3. Cost functions scenario 3

In scenario 3, it is assumed that all collected ocean waste will be reused. This means that storage costs do not have to be taken into account in this scenario. Furthermore, the recycling cost can be further specified into sorting cost onboard, plastic net-treatment costs and the recycling costs of the fishnets and ropes. Production and revenues costs and gains are further specified.

$$Cost = tranport\ costs\ from\ GPGP\ to\ Tanjung\ Priok + port\ handling\ costs + hinterland\ transport\ costs + recycling\ costs + production\ costs - Revenues\ from\ recycled\ products$$

$$Port\ handling\ cost\ Tanjung\ Priok = Q * C_{p_{TP}} \tag{2c}$$

$$Recycling\ costs = Sorting\ cost\ onboard + plastic\ net - treatment\ cost + ghostnets\ net - treatment\ costs \tag{11}$$

$$ghost\ nets\ net - treatment\ costs = W * C_{nt_g} * \alpha_{gn} \tag{12}$$

(based on the weight of collected ocean waste adjusted for ghost nets share and the net-treatment costs of ghost nets)

$$Production\ costs\ socks = \frac{1}{6} * W * \alpha_{gn} * Q_s * C_s \tag{13}$$

(based on the potential share of collected ocean waste adjusted for ghost nets used for producing socks, the potential yield from one ton of ghost nets to produce socks and the costs of producing socks)

$$Production\ costs\ carpets = \frac{1}{6} * W * \alpha_{gn} * Q_{cp} * C_{cp} \tag{14}$$

(based on the potential share of collected ocean waste adjusted for ghost nets used for producing carpet, the potential yield from one ton of ghost nets to produce carpet and the costs of producing carpet)

$$Revenues\ socks = \frac{1}{6} * W * \alpha_{gn} * Q_s * P_s \tag{15}$$

(based on the potential share of collected ocean waste adjusted for ghost nets used for producing socks, the potential yield from one ton of ghost nets to produce socks and the consumer price socks)

$$Revenues\ carpets = \frac{1}{6} * W * \alpha_{gn} * Q_{cp} * P_{cp} \tag{16}$$

(based on the potential share of collected ocean waste adjusted for ghost nets used for producing carpet, the potential yield from one ton of ghost nets to produce carpet and the consumer price of carpet).

3.3. Model assumptions

For the economic assessment, an Excel model was created: it integrates a cost model for calculating and compares the unit costs for remanufacturing of different generic structures. The application uses a database containing data on the treatment process, transport, and warehousing (see Table 2). Significant efforts have been made to gather as much as possible reliable and detailed data, however as we are proposing/developing a new logistical structure for the efficient collection and recycling of ocean waste, assumptions had to be made at several stages of the logistics chain. When detailed information regarding the Ocean Cleanup, or other similar initiatives, was missing, assumptions were made based on data from other sources.

3.3.1. Sea transportation costs

Previous research suggested that a product tanker is the most optimal type of vessel to be used for the Ocean Cleanup project, based on the cost and its stability in naval environments (Slat and et al., 2014). The annual ship purchase costs and crew costs are both adopted from the Ocean Cleanup and are respectively US$110,000 and US$140,000. The plastic collection by a single OCS will be 65 m^3/day and it is expected that the system needs to be emptied every 45 days (Slat and et al., 2014). This means a dry volume of 2925 m^3 of plastic waste needs to be transported, excluding additional water necessary to pump the plastic waste from the plastic waste collection system on the ship and off the ship to the mainland vehicles. Data is gathered of different types of small product tankers that serve as

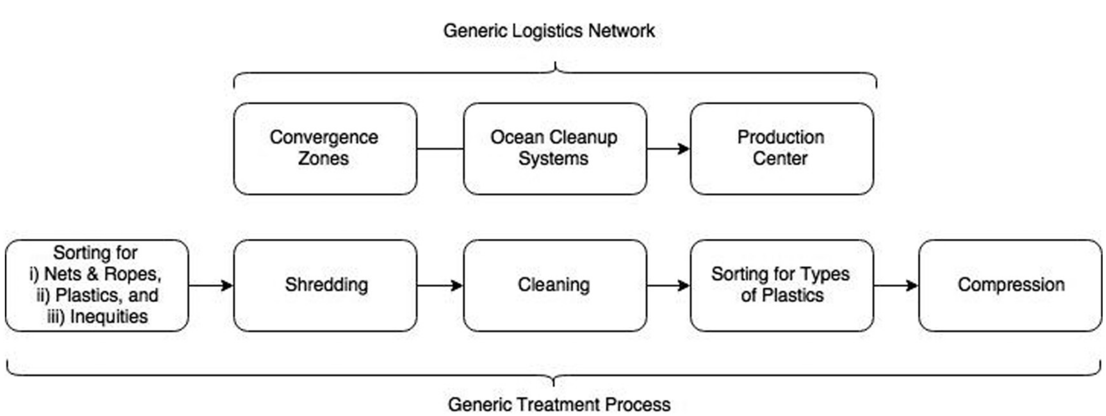

Fig. 7. Structure of the Ocean Cleanup Reversed Logistics Chain.
Source: Adapted from El Korchi and Millet, 2011, Designing a sustainable reverse logistics channel: the 18 generic structures framework. *Journal of Cleaner Production 19*, 588–597.

input for a basis tanker that transports approximately 3000 m^3 of waste for the lowest cost. The most important tanker parameters are the average speed in knots, fuel consumption in tons per day and the cargo hold in cubic meters. This data can be found in Appendix A. Based on this analysis, an average ship capacity (q) of 8500 m^3 is determined with a commercial/door-to-door ship speed (v) of 26.7 km/h, resulting in an average fuel consumption (F) of 12.33 tons/day (while sailing under average speed). A global 20 ports six months average bunker fuel price (IFO380) (P_f) is determined for the period of June 3rd, 2018 up until November 29th, 2019 and was set to be US$ 386.50 per metric tons (Ship and Bunker, n.d.).

3.3.2. Port handling cost & storage costs

A port handling cost for the Port of San Francisco (C_{PSF}) of US$ 1.49/m^3 and a port handling cost for the Port of Esbjerg (C_{PES}) of US$ 4.3 was found. No information regarding port handling costs for the port of Tanjung Priok was found, therefore we assumed an average of the other two ports, C_{PTJ} of US$ 2.91.

Port Storage costs (C_i) of US$ 8.33 per ton per month were determined based on the Port of San Francisco wharfage 2019 rates. No reliable data for storage costs for the Port of Esbjerg and the Port of Tanjung Priok was found. For this reason, the storage costs of the Port of San Francisco were used for the other ports as well.

3.3.3. Hinterland transport costs

No data was found on distances between ports and subsequent processing centers, and for this reason a distance of 250 km has been assumed which seems a reasonable distance for hinterland end haulage. A sensitivity discussion on this assumption is given in Section 4.2. Road transportation costs (C_{rt}) were based on data found by Gradus et al. (2017) and were set on US$ 0.44 per kilometer tons.

3.3.4. Recycling

The ILO (International Labor Organization) has set many international labor standards for seafarers, including minimum monthly wages based on ones function on a ship. Per July 2019, ILO states a minimum daily wage of 20.6US$ for an Able Shipmen, which averages to less than 2.6 US$/h (ITF Seafarers, n.d.). As there is a goal of having a positive social impact, next to the environmental impact, average wages for recycling crew onboard have been set on 5US$/h. As stated before, sorting takes place in a 24-hour operation schedule, meaning 3 shifts of 8 h. An estimation was made for 15 workers for manual disassembly onboard, resulting in 5 workers per shift and an hourly cost of disassembly of (C_{dh}) of US$ 25/h.

Determining the costs of recycling plastics is a difficult process, not only differs this per type of plastic, but fast differences can be seen based on geographical location, this is also mentioned in the sensitivity analysis in Section 4.2. According to Gradus et al., 2017, the remuneration fees (fees for covering the costs of collecting and recycling plastics), given by governments in Europe to municipalities, for recycling plastics can be assumed to be equal to the actual costs involved. These fees, averaged for the Netherlands, Germany, France, and Belgium, are 672 euros per ton plastic. However, these also include collecting costs. Based on their analysis, the average plastic waste collection costs in the Netherlands rounds up to 60% of the total remuneration fees (Gradus et al., 2017). We estimated the plastic net-treatment costs (C_{ntp}) to be equal to the remaining 40% of the averaged remuneration fees, which equaled, adjusted for US dollars, US$ 294 per ton plastic. The approach as set out by Gradus et al., 2017 was used to determine the costs of recycling ropes and fishnets. It was found that an American recycling center paid 330 US$ per ton of ghost nets (Zender Environmental Health and Research Group, n.d.) and that the Korean government reimbursed fisherman with 250 US$ per ton of ghost nets (Dong-Oh, 2009). The fishnets and ropes recycling costs (C_{ntg}) were estimated by averaging above remuneration fees, resulting in average costs of 290 US$ per ton of ropes and fishnets.

3.3.5. Production costs

Production costs of recycled glasses were estimated by analyzing Grandvision's 2016 yearly financial statement (Grandvision, 2017). Grandvision sells almost 14 million glasses worldwide annually and was therefore deemed a reliable source. Based on this analysis and adding a correction factor, an average combined production, marketing, and selling costs (C_g) of US$ 46 was found. No reliable information could be found on the production costs of either (recycled) socks or carpets. As socks are mass-produced items often selling for the cheapest price, and thus revenues are most likely limited, an assumption was made that their production costs would be 95% of their retail price. For recycled carpets, we assumed a production cost of 50% of its retail price.

3.3.6. Revenues

Roughly 10 kg of ocean plastic waste is needed for the production of one pair of recycled glasses (The Independent, 2017; Refinery29, 2017). Furthermore, it was found that one ton of fishnet can be used for either 26,000 pairs of socks or 250 m^3 of carpet (adjusted for a fiber density of 2400 g/m^3) (EcoClub, 2017).

Sea2see and NortonPoint are both companies that already sell glasses made from recycled plastics (Sea2See, n.d.; Norton Point, n.d.). An analysis of their websites resulted in an average product price (P_g) of 100 US$. As no data is available on how many recycled glasses are being sold worldwide, or what their potential is in the market, an estimation is made that there is a yearly market for 100,000 recycled glasses, which is a modest estimation based on the potential.

A retail value of 1 US$ per pair or recycled socks has been assumed, whereas the retail value of recycled carpet is set on a real retail value of 37 US$/$m^2$ (Sneltapijt, n.d.). Again, no data is available on the market for recycled socks or carpet and thus an assumption is made that one-third of the available ocean plastic waste will be sold in the form of socks (1/6th) and carpets (1/6th). Lastly, a study by Themelis and Mussche (2014) reported that one ton of non-recycled plastics (black-plastics) used for incineration has the same value as 1,4 tons of coal. As coal has roughly a value of 64 US$ per ton, this means that black-plastics used for incineration have a value of 89,6 US$ per ton (Themelis and Mussche, 2014). As black-plastics are difficult to sort and recycle, no other reliable data is found for its value. For this reason, we adopted the value of 89,6 US$ per ton.

3.4. Model constraints

As this paper analyzes a novel approach to ocean waste collection and recycling logistics, certain system boundaries were created in the modeling.

3.4.1. System operations

The costs objectives within this paper are analyzed through looking at every process within the reverse logistics supply chain, however the system operations and cost of deployment of the ocean cleanup systems are not included. As these technologies are still being developed and tested, no reliable data can be found.

3.4.2. Recycling and production costs

The recycling of the collected ocean waste is highly dependent on the state the waste is in. Plastic that is highly deteriorated might not be able to be used for recycling, and thus potentially limits the revenues that can be created through recycling and selling products. As discussed before, the business case of recycling ocean plastics depends on collection costs, transport and logistics costs, the costs of aborting and re-use and the part of the ocean plastics that can be reused. Actual dynamics of plastic recycling, in terms of costs per location and potential use is outside the scope of this paper.

Table 2
Input data for the reverse logistics chain (RLC) for the three scenarios.

Input variable	Notation/unit	Value[a]	Sources[b]
Sea transport			
RLC cycle duration	τ (year(s))	1	
RLCs total cycle volume	Q (m^3/year)	23,440	(Slat and et al., 2014)
RLCs total cycle mass	W (tons/year)	7032	(Slat and et al., 2014)
Days between scheduled departures between hubs	h (days)	45	(Slat and et al., 2014)
Number of cycles per year	CY (–)	8.11	
Ship purchase costs averaged over 10 years	Csh (US$/year)	110.000	(Slat and et al., 2014)
Crew costs transport ship	Ccr (US$/year)	140.000	(Slat and et al., 2014)
Ship capacity	q (m^3/ship)	8500	See Appendix A
Distance between the collection site and port	$d_1/d_2/d_3$ (km)	2000; 12,500; 17,000	(SeaRoutes, 2019)
Average commercial/door-to-door ship speed	v (km/h)	26.7	See Appendix A
Fuel consumption ship under the average speed	F (tons/day)	12.33	See Appendix A
Fuel price (IFO380)	Pf (US$/ton)	386,50	(Ship and Bunker, n.d.)
Port handling			
Port handling cost San Francisco	Cp_sf (US$/m^3)	1,49	(San Francisco Port Commission, 2019)
Port handling cost Esbjerg	Cp_es	4,33	(Port of Esbjerg, 2019)
Port handling cost Tanjung Priok	Cp_tj	2,91	Assumption
Hinterland transport			
Distance between port and processing center	d_h (km)	250	Assumption
Road transport cost	Crt (US$/ton-km)	0.44	(de Jong et al., 2011)
Storage			
Inventory cost at the storage site	Ci (US $/ton/month)	8,33	(San Francisco Port Commission, 2019)
Recycling			
Sorting cost onboard (manual sorting)			
Hourly cost of disassembly (3 shifts of 5 workers)	Cdh (US$/h)	25	Calculated
Number of workers for manual disassembly	Nw (# of workers)	15	Assumption
Cost worker per hour	Cw (US$/h)	5	(ITF Seafarers, n.d.)
Time of disassembly for shipping to Esbjerg	Ts (h)	468	Calculated
Plastic net-treatment cost (recycling)			
Net-treatment cost plastic	Cnt_p (US$/ton)	294	Adapted from: Gradus et al. (2017)
Ghost nets net-treatment costs			
Net-treatment cost ghost nets	Cnt_g (US$/ton)	290	Adapted from: Cho (2011), Cho (2009), & Zender Environmental Health and Research Group (2012)
Production			
Glasses	Cg (US$/pair)	46	(Grandvision, 2017)
Fishnets & ropes (socks)	Cs (US$/pair)	0.95	Assumption
Fishnets & ropes (carpet)	Ccp (US$/m^2)	18,7	Assumption
Revenues			
Recycled glasses price	Pg (US$/glasses)	100	Adapted from: Sea2See (n.d.) & Norton Point (n.d.)
Volume of glasses sold per year	Vg (# of glasses)	100,000	Assumption
Fishnets & ropes (socks)	Ps (US$/pair)	1.0	Assumption
Fishnets & ropes (carpet)	Pcp (US$/m^2)	37,4	Adapted from: Sneltapijt (n.d.)
Yield from 1 ton of ghost nets	Qs (pairs of socks)	26,000	(EcoClub, 2017)
Yield from 1 ton of ghost nets	Qcp (m^2 of carpet)	250	(EcoClub, 2017)
Black-plastics	Pbp (US$/ton)	89.6	(Themelis and Mussche, 2014)
Division of waste			
Ghost nets	α_{gn} (%)	52	(van Engelshoven, 2017)
- Fishnets	α_{fn} (%)	37.2	(van Engelshoven, 2017)
- Ropes	α_{rp} (%)	14.7	(van Engelshoven, 2017)
Rigid plastics	α_{pl} (%)	47	(van Engelshoven, 2017)
- Black plastics	α_{bp} (%)	14.5	(van Engelshoven, 2017)
- Non-black plastics	α_{nbp} (%)	32.6	(van Engelshoven, 2017)

[a] A conversion rate of 1.10US$ to 1€ was used throughout this paper.
[b] See Section 3.3 for a detailed description of how data was adapted from sources and how assumptions were made.

4. Evaluation Ocean Cleanup logistics structures

The costs of the Ocean Cleanup logistics structures reflect relevant costs necessary to ship, sort, recycle, and produce new products of the collected plastic and ghost nets waste. The interdisciplinary analysis tries to identify the optimum ocean plastics recycling solution from a technical feasibility, transport and logistics efficient operations, and cost and benefits point of view. The major determinants in the cost calculations are the shipping costs and distances. The sea transport costs are described for a single type of vessel and are analyzed as a function of the trip distance and location. Furthermore, the recycling costs can be divided into the manual sorting costs of the ocean waste and the net-treatments costs of the plastics and the ghost nets. The production costs of recycled glasses are estimated by analyzing yearly financial reports of the large glasses retailer Grandvision (Grandvision, 2017) and by analyzing prices of recycled glasses as given by the companies Sea2See and NortonPoint (Norton Point, n.d.; Sea2See, n.d.).

4.1. Evaluating economic logistics of the Ocean Cleanup

An analysis based on the model input as given in Table 2 and the formulas given in Section 3 suggests that the cost minimization base case, where the ocean waste is either stored or incinerated is - in terms of total economic results – the least pleasant scenario. As the aim of this paper is to optimize ocean waste collection and processing while minimizing costs, it might makes sense to remove the first scenario from this table and from further discussion as it yields a negative outcome. However, the negative economic outcome of this scenario shows the need and importance of developing a processing and recycling chain that creates revenue, in order to make cleaning up the oceans become a viable process, for this reason the first scenario is still shown in the table and discussed.

In scenario 2, where the costs and social impacts are balanced and the ocean waste is transported to the Port of Esbjerg in Denmark, the highest cost are the transport costs (both sea and land transport) and the plastic net-treatment costs. However, the revenues of recycled glasses can be significant, resulting in a positive economic outcome. Furthermore, the analysis suggests that the third scenario, where the focus is on realizing a social impact (through creating local labor and reproduction economies in developing countries) results in the highest annual total costs compared to the first and second scenarios. This is mainly due to the high production costs of recycled socks, carpets and the sorting costs of ghost nets. However, due to the extra revenues created by selling the recycled fishnets and ropes (into socks and carpets) and the plastics (glasses), the overall result of the third scenario (including the additional revenues) is almost a factor 2 higher in comparison to the second scenario. In the third scenario, it is assumed all ocean waste products are reused and sold, therefore, no storage costs are taken into account. As there is no storage in this scenario, this also means there is no change for landfilling, which is an increasingly pressing problem in countries around the world. The third scenario is referred to as a scenario that focusses on creating a 100% social impact, meaning that in this scenario the focus is not so much on saving costs but on creating a sustainable impact on developing countries by bringing in labor and economic opportunities amongst several stages of the logistics chain, such as the sorting stage, recycling stage, and production stage of recycled products. As scenario 3 has an annual positive economic outcome almost twice as large as scenario 2, it can also be suggested that this is the preferred scenario to further develop and research, as it possesses higher potential annual earnings. Based on these findings it can be suggested that the new reverse logistics channel dedicated to the Ocean Cleanup that we propose is an economically and socially viable option to handle the ocean waste that the Ocean Cleanup, and other similar initiatives, intend to collect.

What the table does not show is that – from an economic point of view – the 'best' solution is the do-nothing option as this would mean the cheapest solution in terms of economic value and the safest option in terms of investments. However, this would mean the worst option in terms of marine and social impacts. Although scenarios 2 and 3 appear to carry higher costs, especially the sea transportation costs are not that high. This means that, although the transport of the collected waste should be minimized according to the scientific literature there seems to be room to build a sustainable logistics model based on possible additional revenues to be created from the collected waste (Table 3).

4.2. Sensitivities in the cost model

Several sensitivities can be identified in the analysis, the main variables being transport, sorting of the waste, and production cost. First of all, the assumed load factor of the Ocean Cleanup vessels is quite low (34%). This is because the OCS needs to be emptied every 45 days (Slat and et al., 2014). However, if two systems could be emptied in sequence, or if the ship could be used as floating storage for the OCS, the load factor could increase to 68% or higher, thereby decreasing the sea transportation costs by a factor 2 or more. This would especially have a significant impact on scenario 2, as this scenario has the largest shipping distance. Additionally, hinterland transports costs are quite significant and even higher than sea transport costs in the first scenario. A hinterland transport distance of 250 km was assumed. If facilities could be used that are close to the proposed ports, these hinterland transport costs could be greatly reduced, if not reduced at all. This would especially have a significant impact on the first scenario, though this would still result in an overall negative economic result.

Based on Gradus et al. (2017), we have assumed ocean plastic waste recycling costs to be equal to the renumeration fees given by EU governments to their municipalities to recycling plastics, as this can be assumed to be equal to the actual recycling costs. We have adopted this approach to determine the recycling costs of ghost nets as well. It needs to be noted that determining the actual costs of recycling plastics and ghost nets is a difficult process, as it differs per type of material and location. It thus needs to be noted that these are average recycling costs and could vary significantly.

Outcomes to the recycled ocean plastic glasses production and revenues costs are sensitive to the assumptions we have made. We determined the production cost of glasses and the revenues generated from this by analyzing the financial reports of the glasses retailer Grandvision (Grandvision, 2017) and applying a correction factor of 50% to the selling and marketing costs. Secondly, the number of glasses that can be produced from recycled ocean plastics is limited at roughly 230,000 annually per OCS, based on the fact that 1 pair of glasses can be produced for every 10 kg of collected ocean plastic (Refinery29, 2017; The Independent, 2017). As it is unknown whether there is a market for that number of glasses produced from plastic waste collected from the oceans, we have taken a lower amount of 100,000 classes into account in our calculations. For now, it is unclear if there is a market for that number of glasses produced from plastic waste collected from the oceans. If a much lower number is assumed, scenario 2 will be showing a negative economic result, as there will then not be enough revenues to compensate the recycling and production costs.

Lastly, the revenues of carpets are determined by analyzing the prices of carpets that contained Nylon yarn from recycled fishnets and assuming a correction factor of 50% of the revenue price for the production costs (Sneltapijt, n.d.). An average sales price of 1US$ per pair of socks is assumed, with a 5% profit since this is usually seen as a highly competitive market with low-profit margins. It is assumed that there is a market for 1/3rd of the possible volume of socks and carpets that can be produced from the recycled fishnets and ropes and that this is equally divided into socks and carpets. In the end, this resulted in the assumption that 1/6th of the maximum volume of socks and 1/6th of the maximum volume of carpets will be sold. The assumptions made bring a sensitivity to the analysis, in the sense that it is unknown whether there is a market for these quantities of recycled socks and carpets and production costs could be different, potentially affecting the outcome of the analysis.

5. Conclusions

The main purpose of the paper has been to seek socially acceptable and efficient business solutions for cleaning up the oceans. We developed a bi-objective reverse logistics channel optimizing ocean waste collection and processing while maintaining cost minimization. The main research question in the paper was: 'How to efficiently and sustainably transport, process, and sell plastics from the oceans?'. To answer the research question, an interdisciplinary approach has been developed to analyze the optimum ocean plastics recycling solution from a technical, transport and logistics, and cost and benefits point of view. Plastics for recycling should be collected in each country, but this is often not the case. This has led us to develop a new reverse logistics channel dedicated to the ocean cleanup initiatives, as existing reverse logistics supply chains are not able to capture the specifics of the plastic waste collection out on the ocean. The ocean plastic waste system consists of five central places in the world's oceans where plastic waste concentrates. This means that the collection of waste, in this case, is already 'centralized'. The conventional five-stage approach of traditional plastic waste recycling was redeveloped into our new logistics structure model for the Ocean Cleanup. Based on this newly developed reverse logistics supply chain channel, three different scenarios for transport, storing, recycling, processing and selling the collected ocean waste were formulated. The new logistics network structure for plastic waste collected from oceans and oriented upon 'few-to-few' distinguishes our work from others. The paper also compares and evaluates different lengths of supply chains that handles plastic waste from oceans. The scenarios have been used to build cost models to compare and evaluate the respective scenarios.

Table 3
Results of the respective logistics structures scenarios.

Scenarios/variables	1. Costs minimization (SF, 2000 km)	2. Costs and social impacts balanced (ES, 17,000 km)	3. 100% social impact (TP, 12,500 km)
Costs			
Sea transport	371,168	1,275,986	1,004,541
Port handling	34,926	101,417	68,171
Hinterland transport	773,520	773,520	773,520
Storage	58,577	30,460	×
Recycling			
Manual sorting	×	94,933	94,933
Plastic net-treatment	×	970,277	970,277
Ghost nets net-treatment	×	×	1,060,426
Production			
Glasses	×	4,599,636	4,599,636
Socks	×	×	15,053,168
Carpets	x	x	2,849,132
Total costs (−)	1,238,191	7,846,229	26,473,804
Revenues			
Glasses	×	10,000,000	10,000,000
Socks	x	x	15,845,440
Carpets	×	×	5,698,264
Black plastics	×	91,360	91,360
Total revenues (+)	x	10,091,360	31,635,064
Economic result	−1,238,191	2,245,131	5,161,260

SF = Port of San Francisco, United States; ES = Port of Esbjerg, Denmark; TP = Port of Tanjung Priok, Indonesia.

From this evaluation, several conclusions arise which also contribute to needed changes in current managerial practices to clean up the oceans. Firstly, if only looking at transportation from the collection of ocean plastic waste to the landing of plastic waste it makes sense to minimize the transportation distance and land in San Francisco, as this also minimizes the environmental impact of the transportation part in terms of CO_2 and other emissions. In this paper, the focus is not on profit maximization but instead, it is on cleaning the oceans. It tries to maximize social effects, maximize cost recovery and minimize environmental effects. It shows that when a significant portion of the collected ocean waste is processed and recycled into new products the operation in itself can become viable. However, this assumes that the reverse logistics chain is already in place and functioning efficiently. This means that the involvement of charity to finance the R&D and transport costs will remain needed as long there is not a profitable business model in place based upon revenues from the collected and processed waste.

The sensitivity of the results suggests that transportation costs can be reduced, as well as sorting and production costs. This suggests that careful balancing economic, environmental and social effects to clean the oceans might be possible leading to a sustainable business model for the cleaning up of oceans.

Lastly, it is important to note that though this paper looks at ocean plastic collection and recycling logistics, these recycled plastics are eventually likely to return to the environment in one way or another without proper collection systems in place. This is a topic where consumers, producers and governments need to actively work together to break this cycle.

Several issues for further research can be identified. The cost model optimizes transportation, recycling, processing and selling cost, but only touches upon the potential positive environmental and social impacts. For example, emissions from transportation could be considered but also other environmental influences such as the quality of material as the result of separation method choice and the emissions from each step of the processing in the network are not included in this research, but would be interesting for future research. Furthermore, the environmental improvements to the oceans and the social impacts for emerging economies should be incorporated into further research to arrive at a balanced and sustainable model to arrange for Cleaner Oceans. Another option for further research could be to analyze from a policy perspective if there would be an option to tax consumers, users, suppliers, and others involved with the production, sale, use, and distribution of plastics as a way of dealing with the externalities. In the end, this might provide an income stream to finance the costs of cleaning the oceans.

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Declaration of competing interest

The author(s) declare(s) that they have no competing interests.

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Appendix A. Data of four different small product tankers

	Tanker 1	Tanker 2	Tanker 3	Tanker 4	Average
Length overall (m)	109.92	108.00	111.50	101.39	107.70
Length between perpendiculars (m)	103.18	102.00	106.00	94.90	101.52
Breadth (m)	17.20	19.20	17.60	19.05	18.26
Depth (m)	8.80	9.30	9.00	10.50	9.40
Designed draft (m)	6.50	6.00	6.80	6.50	6.45
Speed (knot)	14.20	12.60	14.00	12.50	13.33
Fuel oil consumption (t/day)	13.00	11.65	–	–	12.33
Endurance (nm)	10,000	7000	4000	5000	6500
Deadweight (t)	7000	6600	7500	7000	7025
Cargo hold (m^3)	8018	8500	8500	9000	8505

Source: Tanker 1: Soli Shipyard. (2007). 7000 DWT IMO ll Chemical/Oil Tanker Outline Specification. SOLI. Tanker 2: Wartsila Corporation. (2006). Wartsila Ship Design, WSD43 6.6K, 6.600 DWT White Oil Tanker Datasheet. Retrieved from Wartsila: https://cdn.wartsila.com/docs/default-source/product-files/sd/merchant/tankers/wsd43-6-6k-white-oil-tanker-ship-design-o-datasheet.pdf?sfvrsn=4; Tanker 3: Taixing Guanghua Shipbuilding Company. (2006). Technical Specification for 7500 DWT Oil Product/Chemical Tanker; Tanker 4: NanJing Tong Kah Shipbuilding Company. (2007). Full Specification for 7000 DWT Oil Product Tanker.

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