TURNING A PROBLEM INTO VALUE – THE CASE OF PLASTIC REACHING THE OCEAN

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TURNING A PROBLEM INTO VALUE – THE CASE OF PLASTIC REACHING THE OCEAN

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ABSTRACT

Economies are rapidly growing. Production and consumption rates are higher than ever before. And the disposal rates are increasing with it, with the absence of any waste infrastructure that can suffice. Global pollution has turned into one of today's biggest threats for the environment, wild life, and humans. This thesis is specifically focussed on the case of plastic reaching the oceans, and how to turn this problem into value. A methodology has been developed to quantify the feasibility and effectiveness of plastic recovery solutions from oceans, rivers and waterways. It was quickly found that no source has been able to capture the totality of the problem of ocean pollution yet. When looking into feasible and effective solutions, the connection between today's status of the problem, the potential barriers, and an investigation of its impact proved to be absolutely crucial. For this specific purpose, several models were developed, including a bow-tie model, the Strategic Solution Space (a summary of essential qualitative factors when designing for high impact), and a trajectory study as a foundation for research. These all combined supported the development of a methodology for assessing plastic recovery solutions; incorporated in this approach are a high level technology screening, a qualitative judgement of benefits, and two case studies of the most favourable concepts. Eventually, turning the problem into value is embodied by guidance in design of recovery solutions, identification of the most important parameters and its relations, a description of the willingness-to-pay, and lastly, recommending the greatest needs in scientific research. Altogether, the combined value presents the ultimate incentive to act.

There is only one type of waste – the waste of time.

PREFACE

We live in times of immense growth and prosperity, where having and possessing are some of the main drivers of today's world. But this all comes at a high price. The world is suffering. Pollution and health risks for both humans and wild life are quickly increasing. On a personal level, it seems like there is not much we can do if we really want to improve matters. To me, this led to a great frustration that eventually motivated me to dedicate my master project to this purpose: hopefully to make things a bit better. Fortunately, there were many people who supported and joined me in this mission.

First of all, I would like to thank the committee. Prof. Hopman, thank you for making the time and effort to step in as the chair during the last phase of my master project. Prof.dr. Van de Voorde and Ir. Frouws, thank you very much for sharing your knowledge and expertise with me. I am very grateful for all times you have challenged me to push the limits.

Furthermore, I would to express my appreciation to DNV GL: The Maritime Advisory Department for providing me with a place to work and unlimited access to maritime advice. I would like to thank Jens Laugesen, Øyvind Endresen, Eva Seides, Bjørn Haugland, Per Marius Berrefjørd, Bente Pretlove, Fenna van der Merwe and Atle Ellefsen for their time and insights they were all willing to share with me.

Esther and Maurice, thank you for the study group during the last months of our theses. It was incredibly uplifting to start each day with bad coffee and a good laugh.

My dear parents, thank you for your endless support and your always welcoming home.

Maarten, after all the years in Delft we can finally say that we turned our masterplan into a success! Thank you for all your big brother love.

Peter, thank you for your love and patience. Your understanding made everything so much easier.

Lastly, I would like to express my deepest gratitude to Arnstein Eknes, my daily supervisor from DNV GL. It was a great honour to work for you and learn from you. I simply cannot imagine a better way to finish university.

Vera

THE STORYLINE

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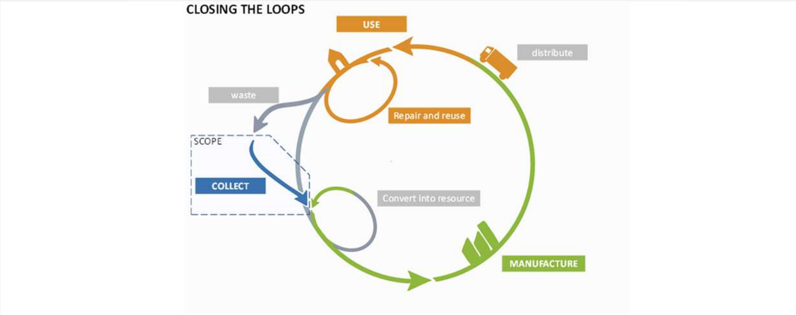
SCOPE

A circular economy refers to an economic and industrial system that is based on the reusability of products and raw materials, and the restorative capacity of natural resources. This thesis focusses on the re-entry of wasted material back into the circular economy. More specifically, the scope looks into the feasibility and effectiveness of plastic recovery solutions from oceans, rivers and waterways.



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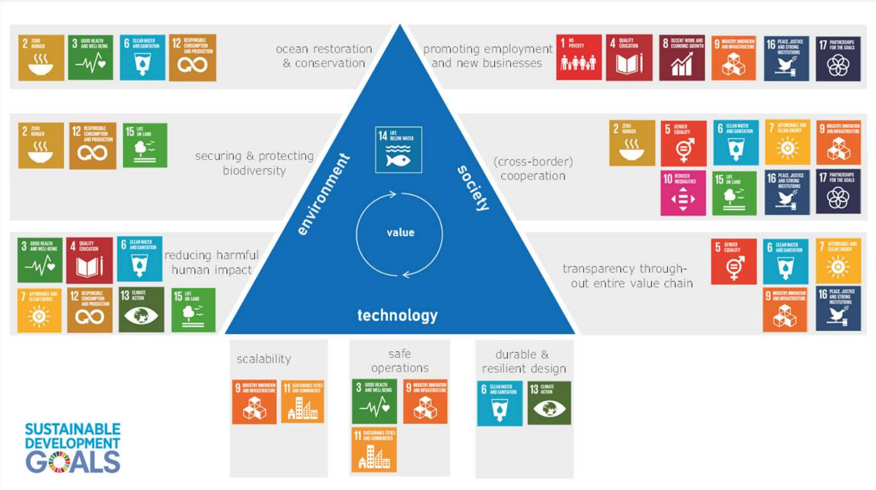
LITERATURE STUDY

The literature study aims to capture the totality of the problem for ocean pollution caused by plastics. Parameters were established that can be seen as the most important contributors to effective and feasible solutions for plastic recovery. The parameters are a balance between technological feasibility, environmental factors and societal involvement. This all together is captured in the Strategic Solution Space (see below), which functions as the foundation of subsequent steps in this research.



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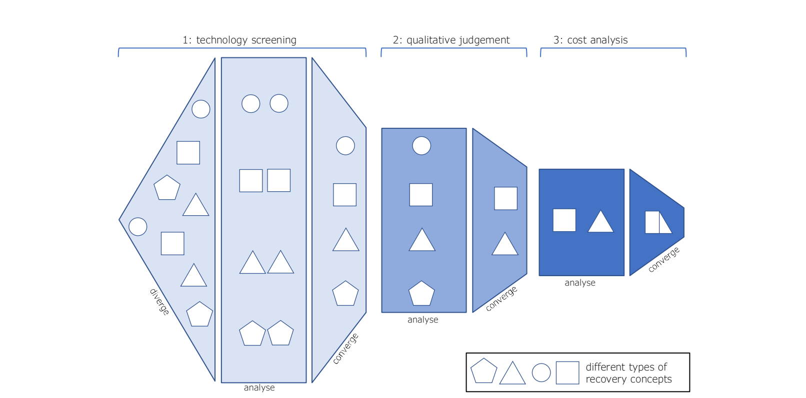
METHODOLOGY

A methodology was developed as a design-support basis for ocean plastic recovery solutions, where the previously found parameters are used as criteria during this assessment. This methodology has three main steps: the first step is a high level technology screening, then a qualitative judgement by experts, and thirdly the case studies of the two most favorable concepts.



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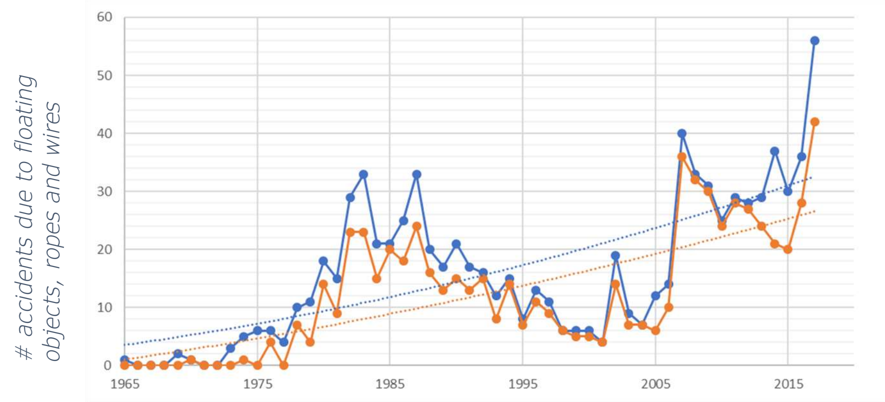
DESIGN RECOMMENDATIONS

In this final phase the findings are used to formulate recommendations for ocean plastic recovery approaches, including recommendations for the main stakeholders such as the UN, IMO and the industry. This phase also addresses the willingness-to-pay – the additional financial contributor related to the indirect cost and indirect benefits of social business cases. Usually, these benefits are not immediately noticeable, but do improve matters in the long run. These are additional costs and benefits incurred by (the mitigation of) accidents, environmental damage and impacts on the quality of life.



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1 INTRODUCTION

Marine life is facing irreparable damage from the millions of tonnes of plastic waste which end up in the ocean each year, the United Nations has warned. According to a scientific study, 4.8 to 12.7 million metric tonnes of plastic currently end up in the ocean every year (Jambeck *et al.*, 2015). Most plastics do not bio-degrade but are broken down into smaller pieces, accumulating in ocean sediments and entering the food web. This type of pollution is disturbing ocean ecosystems and resulting in an increasing health risk for humans (United Nations Global Compact, 2016). The larger pieces of plastic have also led to many hazardous events caused by collision and blockage of propulsion systems.

Among others, the International Maritime Organization (IMO) has been taking action to address the problem, including regulating the discharge of garbage from ships, but also supporting research work. The IMO has labelled marine litter as one of their 'in focus' problems, candidly describing the extent of the problem, and encouraging organizations, companies and general public to take responsibility (IMO, 2016), (IMO, 2018a).

Tackling marine plastic pollution requires some original solutions. As it is a cross-border phenomenon governments are failing to act and business driven initiatives have a stronger likelihood of being successful. The most effective and feasible plans are the most likely to attract potential investors. This thesis will aim to assess solutions by quantifying their feasibility from a clean-up rate and business case potential. A fundamental element of any viable plan should rely upon the reintroduction of marine plastic pollution into a circular economy (see scope of work for further explanation). The goal of this thesis is to develop a methodology assessing the feasibility and effectiveness of plastic recovery solutions for oceans, rivers and waterways. The thesis objective is formulated as:

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1.1 SCOPE OF WORK

As mentioned in the introduction, a viable plan must rely upon the reintroduction of marine plastic pollution into a circular economy (Figure 1.1); an economy that refers to an economic and industrial system that is based on the reusability of products and raw materials, and the restorative capacity of natural resources. Waste flows will turn into an entirely different concept than it is known to be today. The Netherlands Organization for Applied Scientific Research (TNO), argued in a report entitled 'Opportunities for a circular economy in the Netherlands' that a more circular economy could generate a potential added value of €7.3 billion and create 54,000 new jobs (TNO, 2018). However, the current waste infrastructure is linear where the plastics are wasted after a single use. The transition from a linear to a circular economy creates a highly complex challenge, a "wicked problem". But apart from the complex challenges it causes, it also creates room for many opportunities and improvements. This thesis will focus on one opportunity in particular: the recovery of discarded plastics from oceans, rivers and waterways. Collecting the plastics is one of the important challenges to solve towards closing the loop, because it has the potential of adding (a monetary) value to the transition to a circular economy.

Within the chain of collecting plastics, the scope will cover an assessment of solutions that recover plastics by collecting and removing from oceans, rivers and waterways. This assessment will be based on a to be developed approach quantifying the feasibility and effectiveness of solutions. Solving this particular challenge will create more guidance during the design of future solutions by knowing how to effectively turn the problem into value.

The rest of the loop is excluded from this thesis. It is important to mention that the other chains (such as the need for a proper breakdown of plastics to a base material - see green arrows in the figure; or the need for better repair and reuse of products - see orange arrows) have a similar and essential role in closing the loop, but will not be the focus during this thesis.

Summarizing, the main motivation to focus on plastic recovery from oceans, rivers and waterways:

- Promoting re-entry of wasted materials into a circular economy,
- Risk reduction for wild life, nature and humans,
- Promoting a sustainable new market and businesses for an improved waste management infrastructure.

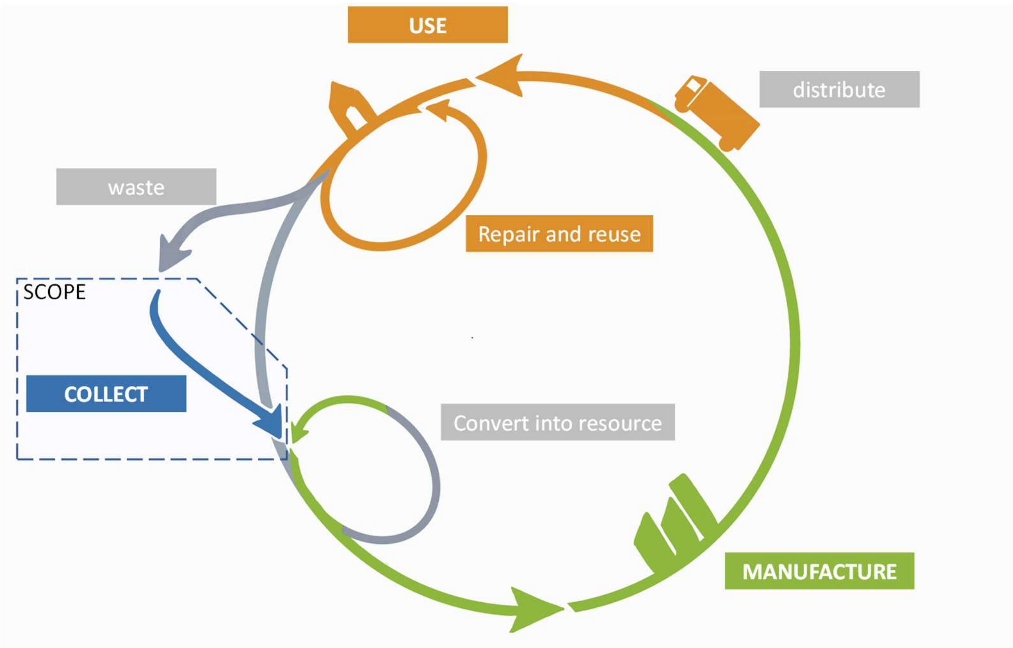


Figure 1.1 Circular economy for plastics; ©Vera Terlouw

1.2 REPORT STRUCTURE

The thesis objective is built up in three phases:
Phase 1 describes and defines the problem of plastic reaching the oceans. Here a definition of the actual plastic waste problem will be obtained by identifying its hazards, causes, consequences – the-state-of-the-art. This phase is based on a combination of literature research and qualitative interviews with people from the industry. The outcome of this research identifies the main parameters contributing to the feasibility and effectiveness of plastic recovery from marine and coastal environments. Phase 2 will describe the development of an approach for assessing solutions intended for plastic recovery from oceans, rivers and waterways. This approach is threefold, starting with a high level screening of technologies, then a qualitative multi-criteria analysis and thirdly a detailed case study of the two most favourable concepts. Phase 3 summarizes guidance for future designs and development of recovery solutions. This includes a recommended approach to determine the willingness-to-pay, an overall conclusion and discussion, and most importantly, it identifies and reports the greatest needs in scientific research. More details about the original graduation workplan can be found in Appendix 1.

Next to these phases, the report uses several other indicators. The references (by an author, year) for the used resources, footnotes[X] to refer to interviews, and **ADDED VALUE** to emphasize the added value for specific parts of this project.

PHASE 1/3

This part of the report describes the results of the literature research. The research is structured by a holistic research statement. In order to structure the different layers of information, the statement is broken down into sub-questions inspired by the structure of a Formal Safety Assessment. The overall goal is to investigate the state-of-the-art of plastic waste recovery, so that the main design parameters can be identified in order to develop a methodology quantifying the feasibility and effectiveness of plastic recovery solutions from oceans, rivers and waterways. The first sub-question that was answered was what kind of causes, hazards and consequences are known. A bow-tie model (Figure 2.4) was used to connect all those parts into an overall hazard identification. Both proactive and reactive barriers can be put in place to stop the worst consequences from happening – such as potential loss of life, harm and reduction of biodiversity, increasing human health risks and loss of income for many different industries, see paragraph 2.2.3 for a further explanation.

Secondly, the most recent estimation of the actual size, distribution and impact was formulated by considering several scenarios by development of a first event tree (Figure 2.7). Investigation shows that in 30 years' time, the mass of ocean plastics will have surpassed the mass of fish and 99% of the water will be polluted. The risk can be reduced by actively incorporating barriers. Global models and big data collection can contribute to effective reduction of these risks by reasonably accurate estimations of highly concentrated areas, see paragraph 2.3.3.

Thirdly, the research showed how leading maritime organizations formulate the problem, rate it importance and describe their future approaches. New technologies were briefly considered as well. It can be concluded that there is a discrepancy between the viewpoint of leading maritime organizations and the industry itself. However, in order to control the risk, both are necessary. It was found that any technology should have a robust foundation connecting on a technological, financial and social level, see paragraph 2.4.

The fourth and last sub-question addresses the parameter identification for potential benefits and costs. Elaborating upon the findings of the third question, it was found that for every new technology the investment and operational costs should be balanced with the risk reduction it is evoking, see paragraph 2.5.4.

The research statement was covered by answering the sub-questions. The state-of-the-art was mostly covered by the first and second sub-question, and the parameters by the third and fourth. **ADDED VALUE:** The most important parameters were identified as a combination of qualitative values addressed on a technological, environmental and societal level. Several quantitative variables were identified as well, such as the operational expenses, investment costs and an estimated recovery potential for every solution.

These parameters will be used in Phase 2 and 3, where the methodology for quantifying the feasibility and effectiveness of recovery solutions will be developed and assessed.

It takes about 2 minutes to read this page. In the same time, 38 tonnes of plastic has entered the oceans (calculation based on data from (Jambeck *et al.*, 2015)).

2 LITERATURE RESEARCH

The main goal of this research is to determine the main factors, the design parameters, which contribute to the effectiveness and feasibility of plastic recovery solutions. Before doing so, the problem itself should be well understood and formulated, and it should contain a recent estimation of the extent of the problem and the status of solving it. The research structure is inspired by the Formal Safety Assessment (FSA), which is widely applied by leading maritime organizations. The way of structuring is particularly relevant in terms of balancing benefits and costs regarding specific issues in the maritime industry. Considering that this report discusses an early stage assessment of plastic recovery solutions and is not yet discussing detailed steps of the operation, the FSA will be used as a guideline towards obtaining parameters for the cost-benefit analysis.

2.1 RESEARCH QUESTION

The literature research can be described by a holistic research statement, connecting the topic, general question and objective. In order to answer this question, the objective is broken down into sub-questions by the structure of FSA, allowing to structure different layers of information.

Preparatory Step Defining goal and operation.	**THE RESEARCH STATEMENT:** An investigation of the state-of-the-art of plastic waste recovery to find which main design parameters can be identified in order to develop a methodology quantifying the feasibility and effectiveness of plastic recovery solutions from oceans, rivers and waterways.
1. Hazard identification Describing what might go wrong.	**SUB-QUESTION 1** What are the causes of plastic pollution, what are the hazards and what kind of consequences have we seen so far? A bow-tie model will be developed based on the findings.
2. Risk Assessment Assessing how bad and how likely it can be.	**SUB-QUESTION 2** How do the most recent scientific studies estimate the actual size, distribution and impact of the problem? The severity and likelihoods of several scenarios are considered here.
3. Risk Control Options Describing if matters can be improved.	**SUB-QUESTION 3** How do leading maritime organizations formulate the current problem statement and rate its importance, and what are their future approaches? What are current recovery solutions and what is the reasoning behind them?
4. Cost-benefit analysis Analysis of how much it costs and how much better it would be.	**SUB-QUESTION 4** What could be a potential benefit and how can we formulate the costs? This is a preparatory step before entering Phase 2 and 3, which will aim for development of the cost-benefit analysis itself.

These questions will be answered separately in the next paragraphs. The response to the overall research statement is given in paragraph 2.5.

2.2 HAZARD IDENTIFICATION

In order to understand the current state of the problem, it is necessary to understand the origin first. This chapter will discuss the causes of plastic pollution, its hazards and what kind of consequences we have seen so far. Eventually, a bow-tie model is used to connect these different parts as a conclusion.

2.2.1 Terminology, types and breakdown of plastics

The term plastic is clearly defined by GESAMP, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (an advisory body consisting of specialized experts nominated by the Sponsoring Agencies of the IMO, FAO, UNESCO-IOC, UNIDO, WMO, IAEA, UN, UNEP and UNDP), and will also be used throughout this project, citing (GESAMP, 2015): *"The name plastic define a sub-category of the larger class of materials called polymers. Polymers are very large molecules that have characteristically long chain-like molecular architecture and therefore very high average molecular weights. They may consist of repeating identical units (homopolymers) or different sub-units in various possible sequences (copolymers). Those polymers that soften on heating, and can be moulded, are generally referred to as 'plastic' materials. These include both virgin plastic resin pellets (easily transported prior to manufacture of plastic objects) as well as the resins mixed or blended with numerous additives to enhance the performance of the material. Additives may typically include fillers, plasticizers, colorants, stabilizers and processing aids. In addition to the thermoplastics, marine debris also includes some thermoset materials such as polyurethane foams, epoxy resins and some coating films. Thermosets are cross-linked materials that cannot be re-moulded on heating. However, these too are generally counted within the category of plastics in marine debris. Particles in the size range of 1 nm to <5 mm are considered microplastics."*

GESAMP uses a clear distinction between primary and secondary microplastics, based on whether the particles were originally manufactured to be of a small size (<5 mm, such as industrial scrubbers, plastic nanoparticles etc.) which are called primary microplastics, and secondary microplastics result from fragmentation and weathering of any larger plastic item, see Figure 2.1. A difference in behaviour between micro-sized thermoplastics and thermosets is that the thermosets tend to have a higher density and are more likely to sink in seawater (just over 50%) (Moore, 2008). More research confirming this difference was published in 2017 by The Ocean Cleanup, which will be further discussed in paragraph 2.3.1.

Looking at the types of plastics that pollute the oceans, 6 classes can be identified that are dominating the entrance into the oceans: polyethylene (PE, high and low density), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS, including expanded EPS), polyurethane (PUR) and polyethylene terephthalate (PET). Most plastics are usually synthesized from fossil fuels. Recent studies have found that the volume or production trend of particular polymer types does not necessarily correspond with the pattern of plastic litter – many societal, economic, technical and environmental factors are contributing to the distribution and composition of plastic litter. It is an obvious fact that the primary plastics outnumber the larger plastic items in the oceans. However, the primary parts still make up only a small proportion of the total estimated mass (Brown and Macfadyen, 2007). On-going degradation of the secondary plastic material would likely result in an increase in microplastics in the future. Plastics show high

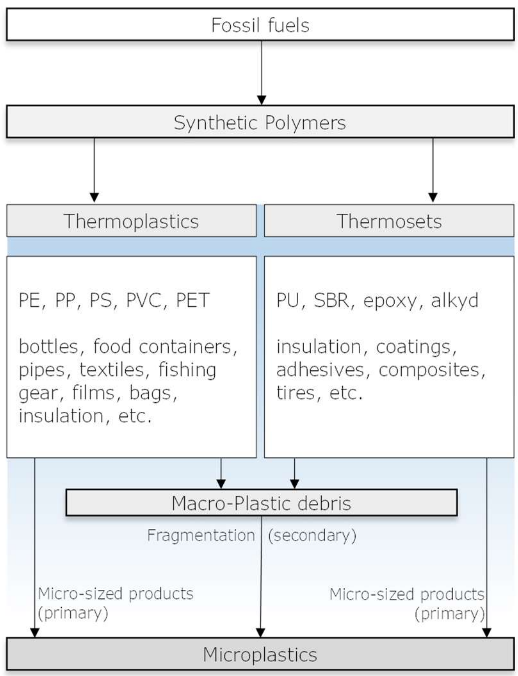


Figure 2.1 Production of the most common plastics including some typical applications, figure inspired by (GESAMP, 2015)

resistance to aging and minimal biological degradation. Especially when exposed to the UV radiation in sunlight, the oxidative degradation of polymers and the hydrolytic properties of seawater, these polymers become embrittled, and break into smaller pieces (Moore, 2008). Photodegradation of common plastics are free-radical mediated oxidation reactions. The corresponding basic reaction is well established, but the knowledge of mechanisms during the advances stages of degradation are still very limited. The reason for this is that studies in the past were very much focussed on the early stages of degradation, since that was likely to happen during the product lifetime, only considering the lifetime of consumer usage. Presently, it is known that degradation typically results in discolouration, development of surface features, becomes weak and brittle in consequence over time. No reliable methodologies to determine the age or duration of outdoor exposure are known or accessible, but it is known that the change of properties and/or fragmentation is highly influenced by polymer type, physicochemical properties and the presence of additives, and can proceed by either abiotic (photodegradation, mechanical, hydrolysis) or biotic pathways (biodegradation). The kinetics of polymer degradation depend on the combination of environmental conditions such as the oxygen concentration, water chemistry, temperature, presence of other chemicals, sunlight, and the community dynamics of degrading microorganisms (Booth *et al.*, 2017). Figure 2.2 shows an example of variation in degradation rates. It shows the different reductions of tensile strength for polymer types in an identical lab setting where the only the concentration of sodium azide, NaN_3, is varied. However, it can be said that there is still a lot to be investigated within this research field. The current research lacks reliable estimations of degradation rates for the entire duration of life and how this is affected by external influences. The degradation rates of different types of plastics are further considered in paragraph 3.1.2 and in the final recommendations.

(Moore, 2008) also expresses his concerns about toxicity, since plastics are known to adsorb hydrophobic pollutants. This means that in case of ingestion, next to blockage and starvation, toxicity is another concern the animals have to face. Paragraph 2.2.3 will further discuss the hazards related to ocean plastics.

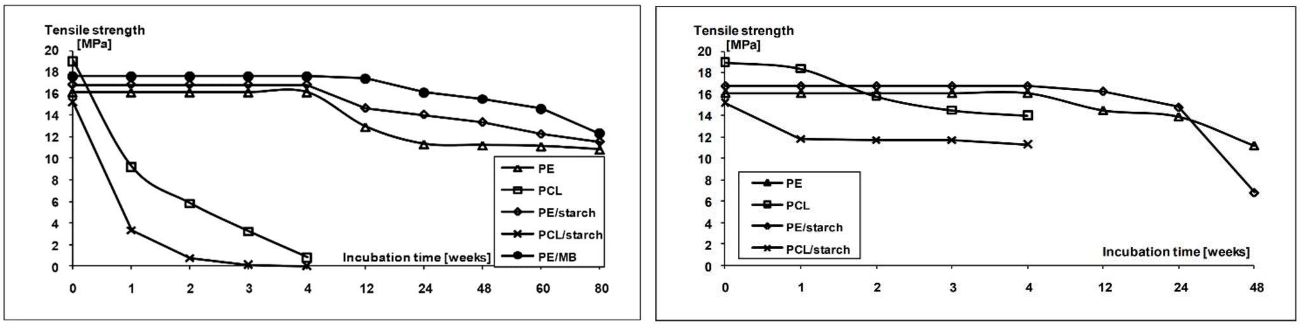


Figure 2.2 Decrease in tensile strength per polymer type during incubation in pure seawater (left) and seawater with NaN_3 (right), courtesy of (Heimowska, Krasowska and Rutkowska, 2012)

2.2.2 Plastic production and pollution over the years

Plastics have been produced on a mass scale since the 1950s with an estimated amount of 8.3 billion tonnes of virgin plastics in history. Half of this material was made in the past 15 years. About 70% of this total number has been discarded, where only 9% has been recycled. Around 12% has been incinerated, but 79% has gone to landfill (Geyer, Jambeck and Law, 2017). From this landfill, a certain part, estimated to be around 8 million tonnes, ends up in the ocean every year, (Jambeck *et al.*, 2015). Figure 2.3 shows the amount of produced and mismanaged plastic waste each year. According to these sources, the main contributors to mismanagement of waste can be found in East-Asia.

Although ocean plastics have been increasing in media attention over the last years (GESAMP, 2015), the problem was already known in the early seventies. Wong was one of the first scientists to publish about the distribution of plastic waste in the Pacific Ocean (Wong, 1974). The paper describes the first quantitative data on tar and plastic waste distribution in the surface waters of the Pacific Ocean. Apart from extensive sampling, it is also striking to see that the hazard of 'small lumps', which we call microplastics nowadays, were already found to be entering the food chain by way of surface-feeding fish and copepods (group of small crustaceans). Wong does not address the cause of the pollution, but he does identify three main factors that influence the global distribution of tar and plastic waste in the oceans. The first factor are the washings caused by oil tankers, second the prevailing winds which are said to be the most impactful in transporting surface pollutants, and thirdly, surface circulation (which are known as the ocean gyres now) also affects the long term distribution of surface pollutants. It is important to mention that the interactions between those three factors are not considered in this research, and the distribution can therefore not be explained to a satisfactory level. Although Wong was not able to map the distributions in great detail, it can be said that he was a pioneer in the field of plastic recovery, challenging many future researchers to continue closing the immense knowledge gaps.

One of the knowledge gaps in this field addresses the origin of the plastics that eventually end up in the oceans. The source of ocean plastic has changed over time (Jambeck *et al.*, 2015). One of the recent sources is the input of plastics from rivers into oceans due to waste mismanagement. Land-based sources are considered the dominant input of plastics into the ocean (Lebreton *et al.*, 2017). As the study of Jambeck demonstrates, the annual flux of litter has been varying between 6.4 and 12 million tonnes since the first research conducted in the 1970s by Wong. In the late seventies, almost all discharges came from ocean vessels, military operations and ship casualties. This discharge of plastic from at-sea vessels has since been banned, but losses still occur – to a much lower extent. Today's litter flux is originating from landfills, due to mismanaged waste as material that is either littered or inadequately disposed (Figure 2.3, larger version in Appendix 2). This waste is not formally managed and included disposal in dumps or uncontrolled landfills, where it is not fully contained (meaning that the waste is not fully closed in and leaks out). The mismanaged waste eventually reaches the ocean via inland waterways, wastewater outflows, and transport by wind or tides. According to Jambeck, the estimates of the mass of plastic waste carried by particular waterways vary in a big range from less than 1 kg per day up to 4.2 metric tonnes per day, from which it can be concluded that it is still very challenging to make a reliable estimation of the amount of plastic waste reaching the oceans.

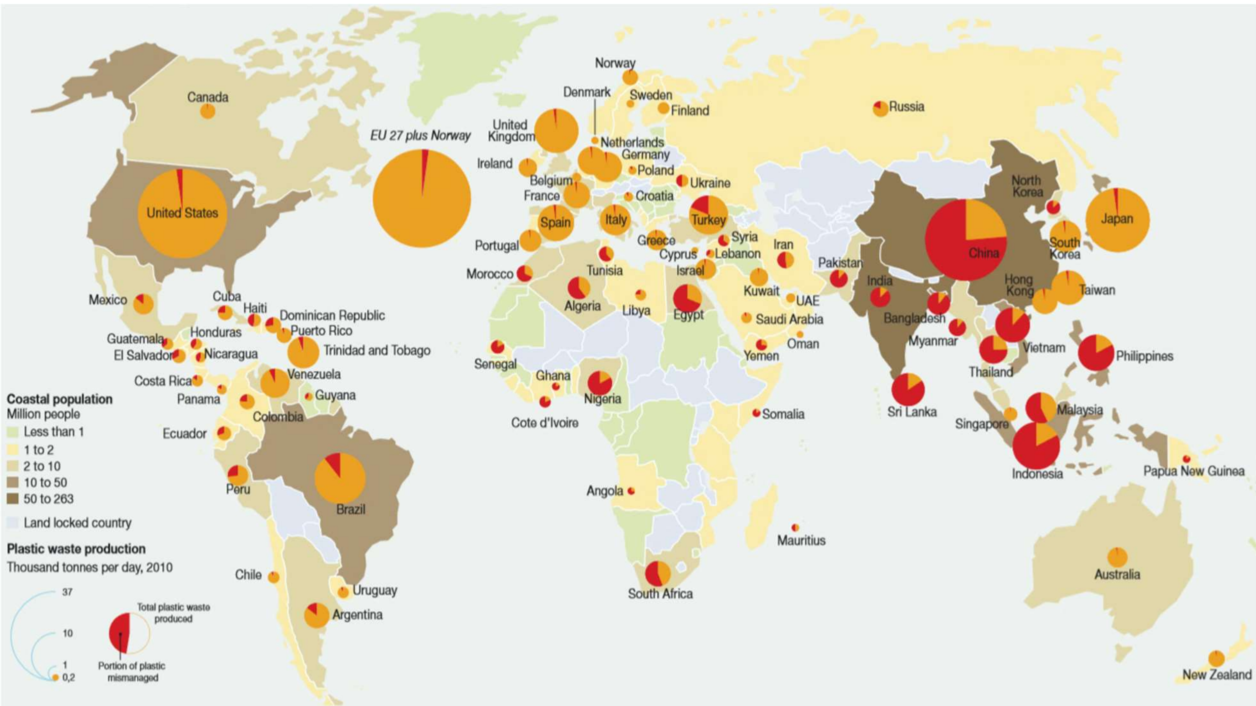


Figure 2.3 Produced and mismanaged plastic waste per annum. Courtesy of (UNEP, 2016)*, information based on* (Jambeck *et al.*, 2015)

Another knowledge gap addresses the consequences of the ocean plastics. One of the most extensive researches is conducted by the Norsk Polarinstitutt, or the Norwegian Polar Institute (NPI). The NPI is Norway's central governmental institution for management-related research, mapping and environmental monitoring in the Arctic and the Antarctic. The Institute advises Norwegian authorities on matters concerning polar environmental management and is the official environmental management body for Norway's Antarctic territorial claims. The NPI conducted a research to determine the state-of-the-art of the ocean plastics, and looked into the causes and consequences for the European Arctic in particular (Hallanger and Gabrielsen, 2018). Next to similar facts and sources as mentioned above, the Norwegian Polar Institute addresses the plastics in the European Arctic including all abiotic environments (non-living chemical and physical parts of the environment that affect living organisms and ecosystems). They found that even in remote locations with relatively low human impact, the densities of plastics found are comparable and even higher than in more urban and populated areas. And those densities appear to be only increasing. In order to compare densities, the fulbar (a seabird) population of different regions is used to compare grams of plastic in their stomachs. In Svalbard, 87.5% of fulmars occur to have plastic in their stomachs, where 22.5% >0.1 gram. Obviously, this does not include or indicate any of the larger plastics, such as floating plastic litter or ghost nets, but it does illustrate the severity of the problem in Arctic regions. Looking at the facts from the NPI, the plastics already seem to be heavily integrated into the Arctic ecosystems. Apart from that, they also mention the negative economic aspect of marine litter and its difficulty to evaluate it. The plastic litter is perceived as aesthetically unpleasant and inconsonant with nature. This decreases the recreational values of areas, which reduces income to the travel and tourism industries. Not to mention the cost of damage and lost cruising time due to entanglement of plastic objects such as fishing gear and ropes with propellers and rudders of vessels.

In order to provide better insight into consequences, the Norwegian Polar Institute mentions that there is a need for a common sampling protocol and standardized methods for quantitative analyses of microplastic in the environment and biodata. Monitoring of plastics should be a standard procedure, and the results should be published yearly and be accessible for everyone. Furthermore, a 6th gyre has been discovered in the Barents Sea. There is a need for validation through observational data.

Surprisingly enough, they do not mention any need for solutions yet. According to the Norwegian Polar Institute the highest priority should be given to filling in the 'huge knowledge gaps' during the coming years (Hallanger and Gabrielsen, 2018). Paragraph 2.4 will discuss whether this corresponds with other mitigation strategies.

2.2.3 Bow-tie Model

A bow-tie diagram depicts the relationships between an identified hazardous event, its causes and consequences and the barriers that have been implemented to reduce the probability of the hazardous event and to mitigate its consequences (Rausand, 2011). In this case, the bow-tie model is applied as a tool to conclude and illustrate the series of activities related to the hazardous event of plastics reaching the oceans. The bow-tie model can be found in Figure 2.4. The contributing factors and events will be discussed step by step.

Specifying the hazardous event (what it is, where it occurs, and when it occurs):	The hazardous event is 'plastics reaching the oceans'. It occurs around the world, throughout the year. This is further examined in paragraph 2.3.3, where global models will be discussed.

Identifying hazards, threats, and triggering events associated with the hazardous event itself:	A hazard is a source of danger that may cause harm to an asset, and a threat is an external or internal source that has the intention and capacity of harming, compromising or stealing the asset specified. The plastics are coming from several sources: from land-based inland sources: 0.5 million tonnes, land-based coastal sources: 9 million tonnes, sea-based sources: fishing litter 1.15 million tonnes, shipping litter 0.6 million tonnes, and primary microplastics 0.95 million tonnes, with the most recent estimated total of 12.2 MT per annum (Galloway *et al.*, 2016). Related hazards are badly managed landfills on shore, quick growing economies and the absence of waste management systems. A recent study shows that the top 10 rivers – eight of which are in Asia – accounting for 88 to 95% of the total global plastic load caused by mismanagement of waste (Schmidt *et al.*, 2017). A threat are companies and factories that dump waste, or fishing gear, without caring about the pollution.
Listing existing and feasible proactive barriers related to the hazardous event and the hazard identified:	Feasible and proactive barriers are: stopping leakage of landfills, management of plastic waste on shore, reduction of waste production, reduction of primary microplastic losses (reducing tyre dust, pellet spills etc). An indirect, but effective barrier is an increase of awareness about the impact of plastic waste. Better understanding from the society will result in a better way of handling waste in their daily lives. This includes awareness programs and integration within education.
Identifying possible event sequences that may follow the hazardous event:	After reaching the oceans, over 90% of the plastic sink (Booth *et al.*, 2017). Associated hazards are toxicity, ingestion and starvation. 5% ends up on the beaches with a distribution of 2000 kg/km^2 (Galloway *et al.*, 2016). Associated consequences are: toxicity, ingestion, starvation, aesthetically diminishing environment, incompatibility with nature, blockage of equipment. Only 1% of the plastics float on the ocean surface, which equals 18 kg/km^2 as a peak concentration in the ocean gyres, global average is <1 kg/km^2. Associated hazards are toxicity, ingestion, starvation, entanglement (Moore, 2008).
Listing existing and feasible reactive barriers/safeguards that may stop the event sequence or reduce the consequences:	Collecting waste from rivers and waterways to stop it from reaching to oceans, development of new rules and regulations, collecting floating and immersed waste from the ocean surface to reduce entanglement and blockage, collecting macroplastic waste to prevent it from breaking down.
Listing of all potential undesirable consequences of the hazardous event:	Undesirable consequences are a potential loss of human life, reduction in biodiversity, human health risks and loss of income (maritime shipping industry, fisheries, tourism), (Hallanger and Gabrielsen, 2018), (Isobe *et al.*, 2015).
Identifying influences from engineering, maintenance, and operational activities on the various barriers:	Influences from engineering could result in both proactive and reactive barriers. Proactive barriers could result in better waste management systems and a reduction of the waste itself. Reactive results in any clean-up facility or collection system (both on- and offshore). New rules and regulations can also act as potential barriers.

Figure 2.4 shows the bow-tie model itself, where the red line represents the worst case scenario. This case is a result of waste that ends up in the ocean by mismanaged waste and illegal dumping and is not collected. The worst case consequences are loss of life (of both animals and humans), because of starvation, toxicity, but also dangerous blockage of maritime equipment. Apart from this potential loss of life, the income of the maritime industry, fisheries and tourism will decrease significantly due to pollution. The mentioned barriers have the potential of preventing the worst consequence from happening.

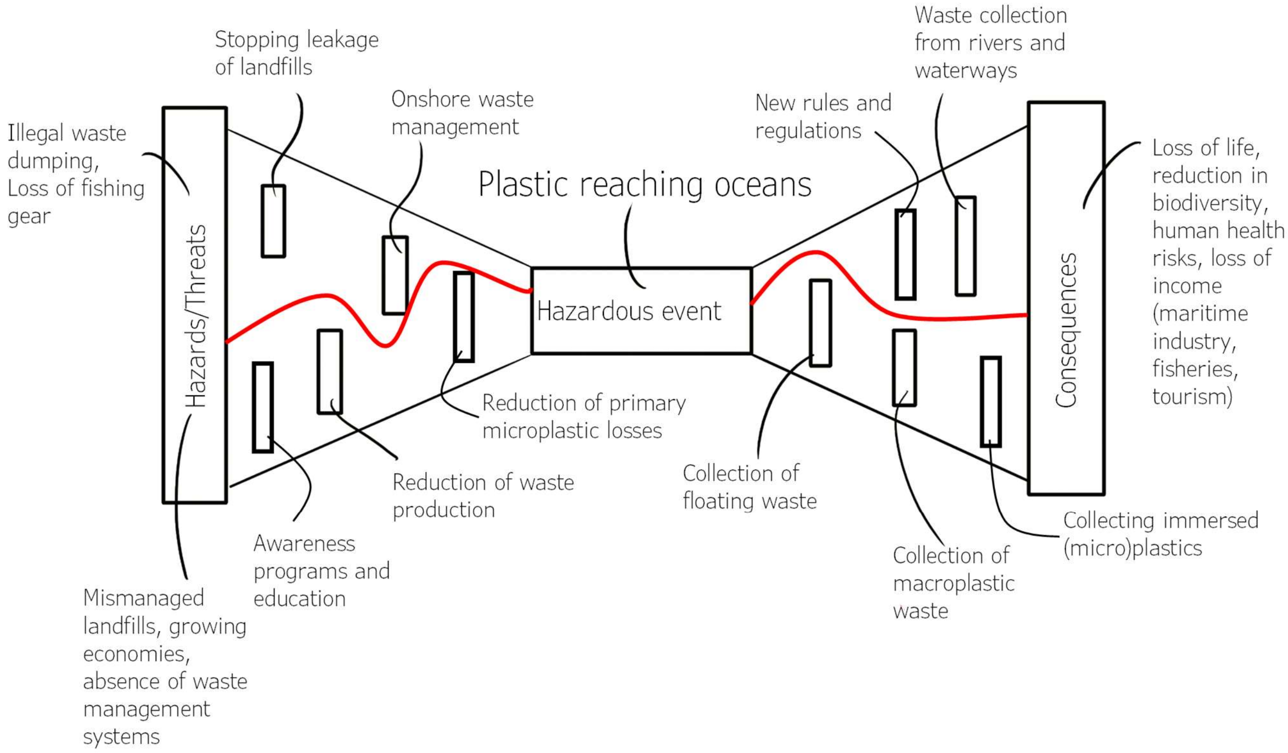


Figure 2.4 Bow-tie model of 'plastics reaching the oceans' with red line as the worst case scenario; ©Vera Terlouw

2.2.4 CONCLUSION SUB-QUESTION 1

The objective of this sub-question was to find and describe the causes, hazards and consequences. The bow-tie model summarizes and connects all contributing factors. From here on, interesting event sequences can be defined and further researched. In further risk assessment probabilities can be linked to the described events. A highly common event sequence starts with an absence of a waste management system as an initial hazard, followed up by leakage of the waste into rivers that flow into the seas, with the main hazardous event as a subsequent step: plastic reaching the oceans. The consequences are immense: potential loss of life, harm and reduction of biodiversity, increasing human health risks and loss of income for many industries. Barriers that can be put into place to reduce the consequences, within the scope of this thesis, are improving the management of waste that has entered rivers. The waste can be recovered at an early stage (when it is entering the rivers), or any subsequent stage. Further investigation of river and ocean models should point out what the likelihood of recovery could be in the different stages.

2.3 RISK ASSESSMENT

This paragraph argues how the most recent scientific studies estimate the actual size, distribution and impact of ocean plastics. It will address today's severity, and how matters can become even worse over time. The likelihoods of several scenarios are considered.

2.3.1 Scenarios and forecasts

In 2015 Jambeck published that without improvements the cumulative quantity of plastic waste available to enter the ocean from land could increase by an order of a magnitude by 2025 (Jambeck *et al.*, 2015). In a business-as-usual scenario the forecast of plastics volume growth, externalities and oil consumption is expected to continue to grow, see Figure 2.5. Several assumptions needed to be made, including that fish stocks are constant (conservative assumption), total oil consumption expected to grow slower (0.5% p.a.) than plastic production (3.8% until 2030, then 3.5% to 2050). Carbon from plastics includes energy used in production and carbon released through incineration and/or energy recovery after-use. The latter is based on 14% incinerated and/or energy recovery in 2014 and 20% in 2050. Carbon budget based on 2 degrees scenario. The plastic production is expected to increase up to 1,124 MT, where the ratio between plastics and fish will be >1:1. Currently, about 95% of plastic packaging material value of $80-120 billion is lost annually after a short first use. Only 14% of plastic packaging is collected for recycling. Only 2% is closed-loop recycled, the other parts cascades recycling or is lost during process, (World Economic Forum, 2016).

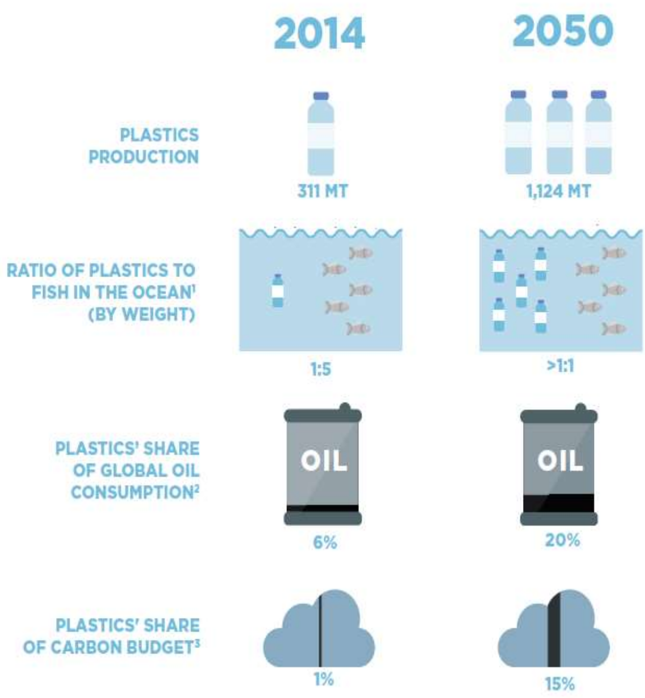


Figure 2.5 Business-as-usual forecast, courtesy of (World Economic Forum, 2016)

The Food and Agriculture Organization of the United Nations (FAO) has identified fishing gear to be one of the most hazardous ocean plastics. Fishing gear is predominantly made of plastic, and when abandoned, lost or discarded at sea, it possesses a serious safety concern for biodiversity, but concerns to navigation too. Entanglement in propellers is becoming a larger issue, and the FAO is developing guidelines helping countries to design effective systems for marking fishing gear so that it can be traced back to its original owner, (FAO, 2018). This hazard was confirmed by one of the most recent publications, where it was stated that ocean plastic pollution within the Great Pacific Garbage Patch is increasing exponentially and at a faster rate than in surrounding waters (Lebreton *et al.*, 2018). Their research is based on multi-vessel and aircraft surveys, predicted that between 45 and 129

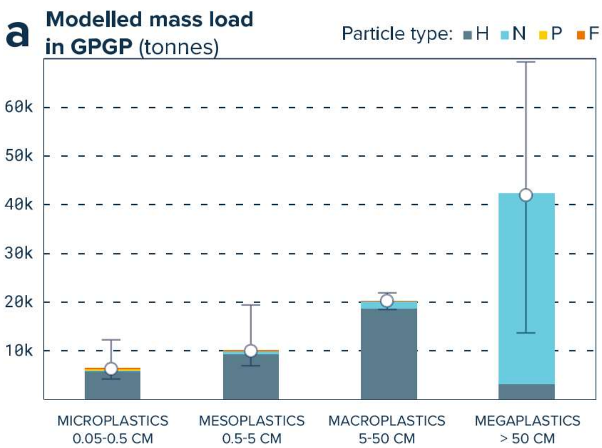


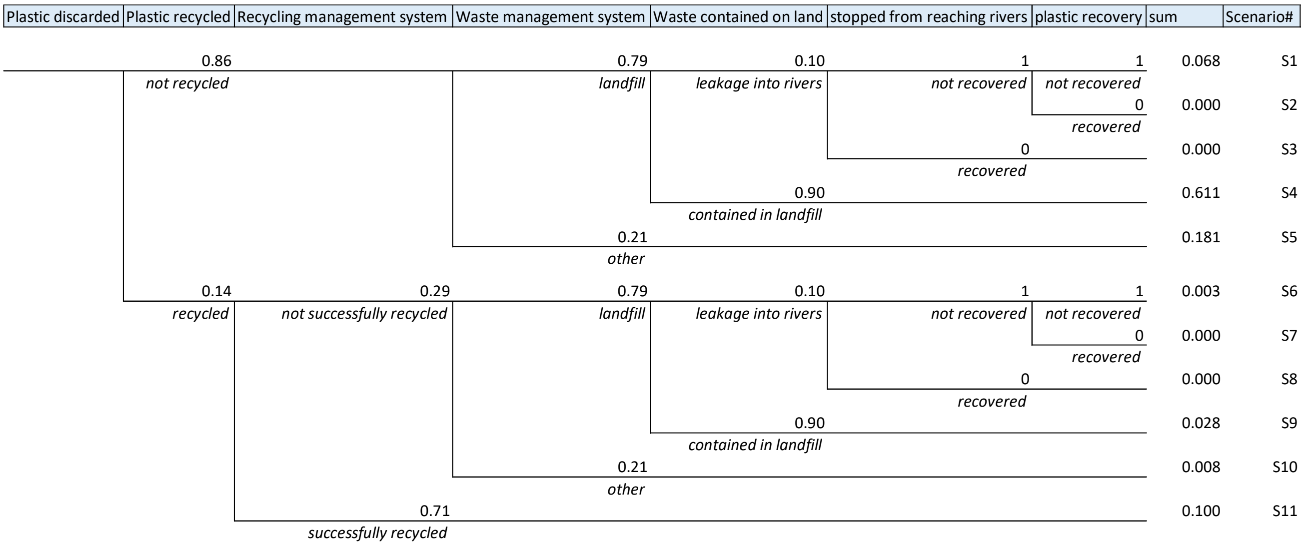
Figure 2.6 Ocean plastic size spectrum in the Great Pacific Garbage Patch, with plastic type H: pieces of hard plastic, plastic sheet and film, N: plastic lines, ropes and fishing nets, P: are pre-production plastic pellets, and F:pieces made of foamed plastics. Courtesy of (Lebreton et al.*, 2018)*

thousand tonnes of ocean plastic is accumulating inside this gyre (which covers an area of roughly 1.6 million km^2). Although this is a very wide range, its lower bound is still four times higher than earlier established. One of the most interesting findings of this very extensive research, is the distribution of the size spectrum, which can be found in Figure 2.6. Striking to see is that more than 75% of the collected garbage was carried by debris larger than 5 cm, and 46% comprised of fishing nets. Only 8% of the total mass accounted for microplastics. Concluding, the loss of fishing gear is another hazardous scenario that should be well-considered.

2.3.2 Event sequences

An event tree is used in order to indicate what kind of risks should be considered for the risk assessment and are worth mitigating later on. The hazards, hazardous event, barriers (both proactive and reactive) and consequences mentioned in the conclusion of the hazard identification (see paragraph 2.2.4) are connected to probabilities in an event tree, see Figure 2.7. In this analysis, the most discussed events and barriers are taken into account. The probabilities that were used are based on the mentioned research results discussed in sub-question 1, and are global averages. The probability of successful stopping from plastics entering rivers, and successful recovery of ocean plastics are both 0 here, since no technologies are applied yet. Considering that the distribution of plastic waste is not homogenous, the final probabilities can only be seen as a rough estimation of the actual risk. What it does show, is the ratio of probabilities between events, and how a possible barrier could change the probability and consequence. For example, the probability that waste is discarded is 0.86. The chance that this piece of waste ends up in the ocean is 0.068. If a barrier would be installed that could increase the probability of recovery to 0.5, the probability of plastics ending up in the ocean could decrease to 0.034.

Although this event tree is currently in an early stage of development, it does illustrate its function as a valuable tool in future to quantify the potential benefit of risk reduction. Better global distribution models and use of data can contribute to the accuracy of this method. Validation of those models is necessary to offer an acceptable level of uncertainty. It is recommended to consider more scenarios, such as the loss of fishing gear, in future.



Scenario#	end event
S1	loss of life, entanglement, breakdown into smaller parts, machinery breakdowr
S2	waste can re-enter circular economy, controlled situation
S3	pollution limited to landbased
S4	discarded in semi-controlled situation
S5	discarded in controlled situation
S6	loss of life, entanglement, breakdown into smaller parts, machinery breakdowr
S7	waste can re-enter circular economy, controlled situation
S8	pollution limited to landbased
S9	discarded in semi-controlled situation
S10	discarded in controlled situation
S11	plastic in circular economy

Figure 2.7 Event tree for plastic reaching the oceans; ©Vera Terlouw

2.3.3 Global models

One of today's most thorough global models of plastic waste unveils its main sources based on geospatial data of population density, rates of mismanaged plastic waste production per inhabitant and per country, monthly catchment runoff and presence of artificial barriers. The amount of plastic that yearly enter the oceans via rivers was estimated to be ranging from 1.15 and 2.41 million tonnes, and most dominantly contributed by rivers of the Asian continent. The top 20 polluting rivers were mostly located in Asia where 21% of the global population lives on 2.2% of the continental surface area. Looking at the 122 top polluting rivers with 4% of the total surface area and 36% of the global population, we find that these are responsible for >90% of the plastic waste inputs (Jambeck *et al.*, 2015). What this research says, is that the concentrations of plastic waste are extremely high in specific areas. This could be an important parameter, but it should be mentioned that these numbers are not validated by any other model or research.

Another global model was developed by The Ocean Cleanup, a Dutch non-profit organization, developing advanced technologies to rid the world's oceans of plastic. They have published several articles, among which they discuss the plastic input from rivers into oceans based on waste management, population density and hydrological information (Lebreton *et al.*, 2017). Although the spread of the data is still large, the research provides baseline data for ocean plastic mass balance exercises. Figure 2.8 shows the flow from the riverine system into the oceans every year. The top 20 polluting rivers were mostly located in Asia and accounted for 67% of the global annual input. Their model was calibrated for plastics ranging between 0.3 mm and 0.5 m. Their estimation is therefore still conservative, since it is excluding microplastics smaller than 0.3 mm and excluding larger pieces, such as ghost nets, and for as far their knowledge is accessible, not properly linked to the model of Lebreton yet (paragraph 2.3.1), whose research was also funded by The Ocean Cleanup.

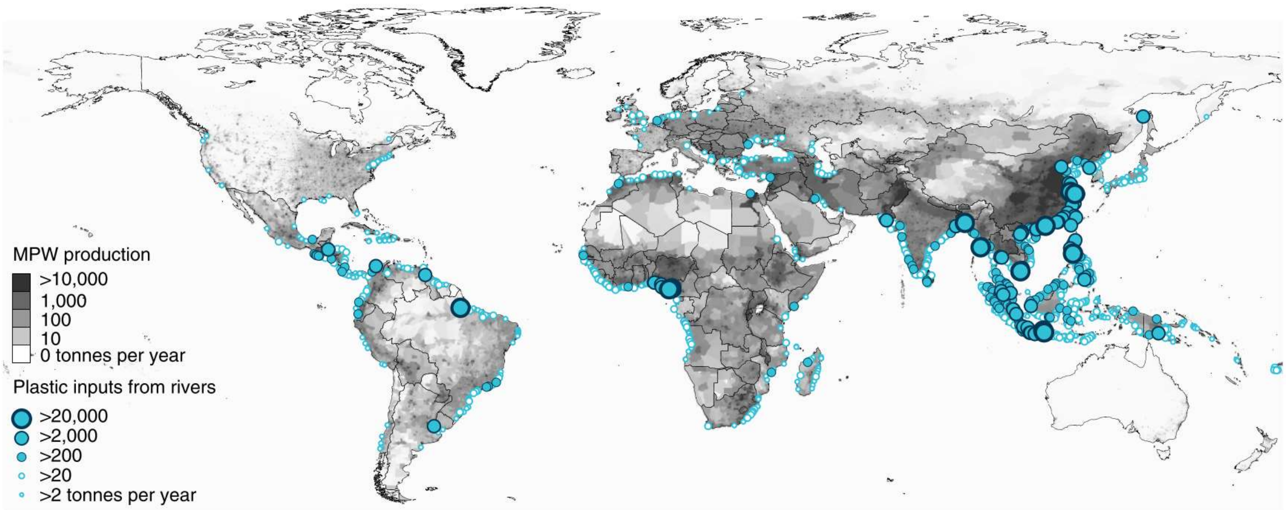


Figure 2.8 Mass of river plastic flowing into oceans in tonnes per year (Courtesy of The Ocean Cleanup)

Oceanographer Van Sebille developed a global model called PlasticAdrift, which is an open-source, statistical model of the surface pathways of the oceans, mapping the likely path and destination of floating debris over a ten year period into the future (*Plastic Adrift*, 2018). Van Sebille used observational data from the Global Drifter Program (a global set of buoys that get advected with the near-surface flow, traced since the 1980s) in a particle-trajectory tracer approach. Unique about his research is that seasonal cycles are included, and an interesting suggestion on connectivity between the 6 gyres, meaning that inter-ocean exchanges play a larger role than was ever expected (van Sebille, England and Froyland, 2012). Figure 2.9 shows an example of Van Sebille's model, where the spatial pattern of leakiness for the six garbage patches is demonstrated.

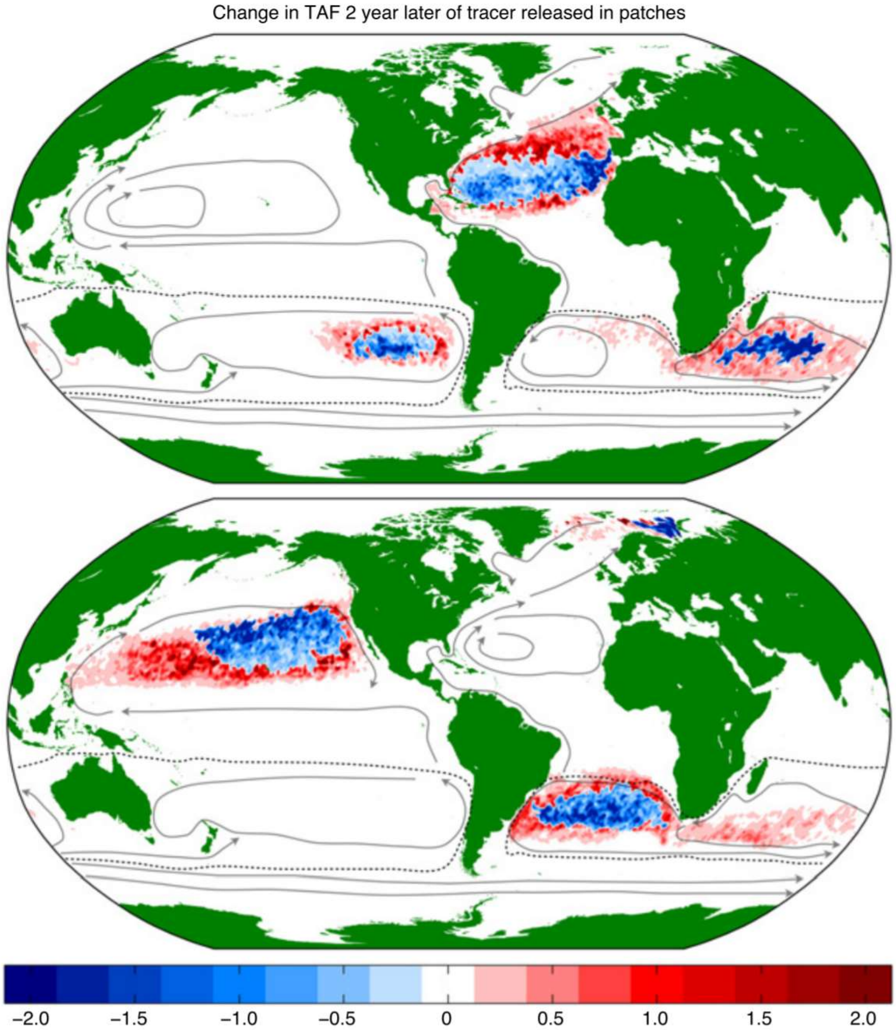


Figure 2.9 The spatial pattern of leakiness for the six garbage patches (Courtesy of Van Sebille)

2.3.4 CONCLUSION SUB-QUESTION 2

Coming back to the research sub-question: How do the most recent scientific studies estimate the actual size, distribution and impact of the problem? It can be agreed upon that the future is not looking bright if the pollution continues at the same pace. By 2050, the mass of ocean plastics will have surpassed the mass of fish and 99% of the water will be polluted. The probabilities of the consequences can be reduced by actively incorporating barriers. Global models and big data collection can contribute to effective reduction by reasonably accurate estimations of highly concentrated areas. However, most of today's global models are based on numerical models, which are in many cases not verified with measurements in the actual problem areas. Today's best practises have only used local measurements of a very few locations, which were extrapolated for their numerical model.

When utilizing these global models, one should be aware and extremely cautious of the uncertainty of the used data. On the other hand, this does create many recommendations and opportunities for future work, such as reliable sources of ocean mapping and sharing.

2.4 RISK CONTROL OPTIONS

Since plastic recovery from oceans, rivers and waterways is a cross-border phenomenon, it is of great importance to understand the perspective from the parties involved in ocean governance, such as maritime organizations, governmental institutions and global organizations. These parties might not be directly involved in the recovery of plastics, but they do possess a strong guiding power. Researching their perspectives and how they rate the importance of this issue, is therefore very meaningful for finding what kind of risk control options would be feasible. The second part of the answer to this sub-question discusses some solutions from the industry and their strategies.

2.4.1 International Maritime Organization

The International Maritime Organization (IMO) is the United Nations (UN) specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships. Its main role is to create a fair regulatory framework for the shipping industry, which can be universally adopted and implemented. Through IMO and the Organization's Member States, civil society and the shipping industry are working together on a continued and strengthened contribution towards a green economy and growth in a sustainable manner. Promoting sustainable shipping and maritime development is one of the major priorities of IMO in the coming years. Therefore, IMO is one of the big parties to consider in plastic waste recovery. Parenté[1] has confirmed that the topic of marine litter is progressing in the IMO, and that the IMO is considering proposals for taking action (IMO, 2018b).

Since IMO is an agency of the UN, the IMO considers the ongoing problem of marine plastic pollution as urgent for the same reasons as the sustainable Development Goal (SDG) 14 target. The SDGs are a collection of 17 global goals set by the UN, covering a broad range of social and economic development issues. SDG 14 sets particular goals to "*conserve and sustainably use the oceans, seas and marine resources for sustainable development*" (United Nations, 2017). Specific pressure was put on the IMO by the UN by *"inviting the IMO and its conventions to increase their action to prevent and reduce marine litter and microplastics and their harmful effects and coordinate where appropriate to achieve this end"* (Marine Environment Protection Committee, 2018). The current IMO regulatory framework on marine plastic litter as contained in MARPOL Annex V is not effective to prevent marine plastic litter coming from ships, which was expressed by the IMO itself in the MEPC72 document (Marine Environment Protection Committee, 2018).

The International Maritime Organization (IMO) has two main objectives regarding plastic pollution in marine environments, citing IMO's Sustainable Development Goal 14 document (Marine Environment Protection Committee, 2018):

- *"The proposed new output will facilitate the effective implementation of the revised MARPOL Annex V and is covered under Strategic Direction (SD) 1 (improve implementation), SD 4 (engage in ocean governance) and SD 6 (ensure regulatory effectiveness)."*
- *"In contributing to assess and continuously reduce plastic pollution in the marine environment, IMO will demonstrate its leadership role as the global regulator of shipping, and address a challenge that affects directly the maritime community and the need to meet the 2030 Agenda for Sustainable Development."*

Meaning that the mentioned revised MARPOL Annex V entered into force on 1 January 2013, prohibits the discharge of garbage including plastic from all ships of every type whatsoever operating in the marine environment. The Strategic Directions (SDs) are IMO internal directions for the organization to go in the next 6 years, further described in (IMO Assembly, 2017), help to enforce the organization's mission statement. The IMO will step into a leadership role and will have to look for solution in how to find direct changes that can be implemented by the maritime community.

[1] Laurent Parenté, chairman of the IMSO, Vanuatu Ambassador and Permanent Representative of the IMO, confirmed the progress of marine litter in IMO on August 15, 2018.

The challenge mentioned in the second objective is the plastic pollution in the marine environment in general, but the 2030 Agenda contains a more tangible contributions to this challenge:
According to IMO, the following aspects that contribute to marine litter are identified as:

- Abandoned discarded or lost fishing gear and fish aggregating devices;
- Mismanagement of marine garbage;
- Accidents involving the loss of containers.

In order to lower the impact of the mentioned aspects, next steps need to be defined so changes can be implemented, considering:

- Assessment of, including through collection and analysis of data, the levels, sources of marine plastic litter and microplastics from offshore, shipping and fishing and their cause (i.e. mismanagement of garbage, loss of cargo, loss of gear, equipment, etc.);
- Identification of the best possible measures and best available techniques and practices to prevent discharges of marine plastic litter and microplastics from ships;
- Adoption of further measures to, in pursuance of SDG 14's target, prevent and significantly reduce marine pollution of all kinds by 2025;
- Determination of other relevant priority areas.

In order to succeed here, an analysis of the implications is required, meaning that there is a need for solutions to cover the cost and administrative burden. Furthermore, the IMO expressed their need for a clear description of benefits of addressing the challenge that affects the maritime community directly.

2.4.2 UNEP, UNOPS, and other UN related organizations

The United Nations Environment Programme (UNEP) is a global leading environmental authority and serves as an authoritative advocate for the global environment. The UNEP has the ability to set standards and structured sustainability measures and by doing so, anticipate and manage emerging environmental, social and economic issues. The overarching principles of UNEP are the precautionary approach and the human rights-approach, which is clearly visible in their focus to address the problem at its source: creating awareness in an early stage of, in this case, the source of plastic pollution, and from there on integrating new sets of standards and measures. A great example of the UNEP's approach on ocean plastic is their #CleanSeas programme, launched in February 2017, with "*the aim of engaging governments, the general public, civil society and the private sector in the fight against marine plastic litter.*" The campaign is addressing the root-cause of the litter by targeting the production and consumption of non-recoverable and single-use plastics. However, for their #CleanSeas campaign, people are going outside with trash bags; it may seem like they are cleaning up the beaches, their actual goal is to create engagement among people, societies and governments. The power of the media is the main power they possess right now, utilizing large-scale media campaigns to create support.

The United Nations Office for Project Services (UNOPS) is another organization committed to UN values, that functions as a service provider, technical advisor and implementer of different projects with the emphasis on bringing peace and security, humanitarian and development solutions to the world's most challenging environments. A fundamental difference with the UNEP is that the UNOPS focusses on operations directly. Yearly they run around a thousand projects for partners, across more than 80 countries. Among those projects, several of them were related to plastic waste management. An example of an implemented project is in Sri Lanka (one of the world's biggest polluters, according to (Isobe *et al.*, 2015) where on behalf of the UNEP to improve solid-waste management, urban surface water drainage and environmental restoration. UNOPS took measures by construction of seven landfills, five recycling centres, five compost facilities and one waste transfer station, where the UNOPS worked closely together with local authorities towards a more sustainable solution for solid-waste management. Financial viability was ensured by support from the EU, which also included an introduction of a user fee for waste collection and the establishment of marketing channels to sell compost produced from collected waste. The UNOPS approach is very much focussed on making local, but fundamental changes. It should be mentioned that this approach is quite challenging to upscale to a global level, but that the combination of local solutions and global application could lead to a solution with great potential.

According to a speech by the UNOPS at the UN Ocean Conference (UN Ocean Conference - Private-sector roundtable on marine pollution | UNOPS, 2017), they are currently looking into how plastics that are already thrown overboard can be caught to possibly reuse. Besides this, they mentioned the need for new partnerships that work to ensure sustainable development of life below the sea. Another great need are new policies, new investments and on-shore projects. The UNOPS claims to be ready to implement these projects and channel investment into initiatives that help restore the vast oceans and life on earth.

The strategy of the UN and its Sustainable Development Goals has been applied to the outcome of the literature study, see paragraphs 2.5.1 and 2.5.2.

2.4.3 G20

The Group of Twenty (G20) is an international forum for the governments and central bank governors from Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, The Republic of Korea, the Russian Federation, Saudi Arabia, South Africa, Turkey, the United Kingdom, the United States and the European Union. The G20 adopted two declarations – the Marine Litter Action Plan and the G20 Resource Efficiency Dialogue. The group seems to have a similar approach as the UNEP by using a set of recommendations in order to promote awareness, but they differ by directly promoting clean-up activities in a planned and consistent manner supporting removal and remediation actions, particularly in highly populated, and touristy, areas (G20, 2017).

The G20 countries confirm their responsibility of setting an example by taking steps towards a transition to a circular economy that reduces marine litter at a much larger scale. One of the outcomes was "*Costs of failing to act are much higher than the costs of action*", but on the other hand they also say that "*the momentum is welcomed but not enough to solve the problem in the upcoming years*" (G20, 2017).

The G20 concluded the convention with a reiteration of the need to address pollution from land based sources and sea based sources, including the fishing, aqua-cultural and shipping industries. Financial resources for cost-effectiveness analyses should be addressed, as well as measures for marine litter prevention or reduction. The area of prior concern is the "*promotion of the socio-economic benefit of establishing policies to prevent marine litter*", meaning that acknowledging and promoting the fact that reduction of marine litter can generate a healthier biodiversity, can cause employment generation, tourism development, sustainable fisheries and better waste and water management. Unfortunately, this was not strengthened by research, but it is an estimated impact of implementation of policies.

2.4.4 Norwegian Shipowners Association

The Norwegian Shipowners Association (NSA or Norges Rederiforbund) serves as support for the Norwegian shipping companies in the development of a safe, environmentally and socially responsible international maritime industry. Environmental protection is one of their main objectives, and is combined with their central position in the maritime industry, an important organization to take into account.

Last year the NSA has on basis of initiative of PGS decided to invite the whole Norwegian Fleet to take part in collection and sharing of all data of the oceans, called the Global Ocean Data Initiative. According to NSA's CEO Sturla Hendriksen: *"The oceans are holding vast arrays of important opportunities to ensure healthy food, new medicines, precious metals and minerals, renewable energy and green* *transportation for a rapidly growing world population. At the same time, the health of the oceans is rapidly deteriorating. Ocean acidification is an urgent challenge, and it is a sad fact that unless we take action, there will be more plastic than fish in the oceans within the next few decades. We must increase our knowledge of the oceans and this initiative will hopefully be a step in the right direction."*

One of the ways to increase the knowledge that was referred to is Automatic Identification System (AIS) ship tracking data from satellites. It enables modelling and geographical allocation of emissions and discharges. The development of a framework for the implementation of this type of data was developed by DNV GL (Mjelde *et al.*, 2014), and could have a possible application in effective ocean plastic recovery. A similar approach has been applied successfully in the oil and gas industry in the past, where great amounts of seismic and surplus data of the oceans like temperatures, salinity, depths, currents and weather conditions, contributed to effective search for oil and gas reserves. By inviting the entire Norwegian Fleet to help gathering data, more knowledge can be gathered and put to a new use.

According to statements that were made by the NSA during several presentations (#ThinkOceans conference 12/04/2018, NSA meeting on 19/04/2018) the association is interested in taking a global leadership position towards cleaner oceans together with the Norwegian government. They show interest in developing a funding mechanism that promotes the use of recovery solutions.

2.4.5 Government of Japan

Next to conventional literature research, other sources of information should be looked after in order to cover a thorough view of the problem. Therefore, the view and actions from the Japanese government are examined, since Japan is taking a progressive and modern role in environmental issues and ability to obtain solutions. Appendix 3 describes a good example by the Japanese government by taking an active role in plastic recovery, where the foundation goes back to cultural values as taking care of nature, and the ability to connect that to a clear role division and proper financing ('Japanese Government on Marine Litter', 2018).

2.4.6 Solutions From Non-Governmental Organizations

Next to the initiatives from the organizations, the market is starting to develop solutions based from local initiatives. This paragraph discusses some of the most interesting and diverse initiative seen so far. Other solutions are included in the solution database, see Phase 2.

DNV GL's Innovation Project: Spindrift

In 2013 the predecessor of DNV GL, Det Norske Veritas (DNV) initiated an internal "extraordinary innovation project" (EIP) with the objectives to design a ship to collect and process the plastic and debris. This included an assessment of the needed total clean-up vessel capacity to effectively reduce/eliminate the present plastic island in the Pacific Ocean within 5-10 years. The project findings were discussed during a conversation with Atle Ellefsen[2]. Looking at their research findings, the EIP was ahead of its time. The team was able to identify the main hazards and effects, such as the entrance of plastic into the food web, affecting humans through bioaccumulation. The numbers that they have found indicating the number of affected species through ingestion and entanglement was lower than recent studies, but this number could have changed rapidly over the years. Overall, the team was able to identify the main influencing factors and make an assessment of its impact. Besides that, they identified the knowledge gaps in that time. Looking back on their results, this project represents a reliable source

[2] Atle Ellefsen is a chief naval architect at DNV GL and was the main designer of the Spindrift Project. This conversation took place on April 16, 2018 in Høvik, Norway.

formulating the state-of-the-art in 2013. As described in their research, the knowledge gaps where that big that they put it as their priority to close some of these gaps first, before looking at clean-up solutions. Their objective was reformulated to creating better understanding on sources, biological impact, relationship between size and transport dynamics, human impact, toxicity impacts and ocean circulation models. Consistent monitoring and sampling methodologies were needed in order to compare results between studies over time. Another gap is the lack of comprehensive and coordinated voluntary and regulatory tools to address the problem. Summarizing, the EIP prioritized filling up these knowledge gaps in order to implement clean-up efforts since environmental and human health risks and technical feasibility of mitigation options will need to be jointly considered.

When they investigated plans of other organizations, they found a similar prioritization. At that moment in time, the emphasis was on doing research. In case solutions were sought, the majority designed vessels that combined research and clean-up, just like the concept solution that was delivered at the end of the DNV project. The solutions of 2013 had more in common regarding their operations; they all focussed on high concentration areas, small debris of >5 mm and macro debris (ghost nets etc.). All solutions would use the collected waste for a similar purpose: the collected material was necessary for research. Organizations that were part of the state-of-the-art here were The Clean Ocean Project, Algalita Research Foundation, UpGyres, PlanetSolar, Gyre Cleanup Plan, Protei, the Yanko Design, Blue Whale Boat & Mediterranean Cleanup and one of the most interesting ones: The Floating Horizon, which appears to be a direct precursor of The Ocean Cleanup's most recent solution.

It should be mentioned that some major assumptions were made during this project, including:

- The plastics and debris have a value in itself as it may be partly recycled or burned in power plants.
- Before the value can be realized the plastics and debris must be collected at sea and brought back onshore.
- Alternatively the plastics material can be converted to energy for fuelling of the on board operations and process plants.
- There would be value added to the marine ecosystems by reducing the amount of plastic in the oceans.

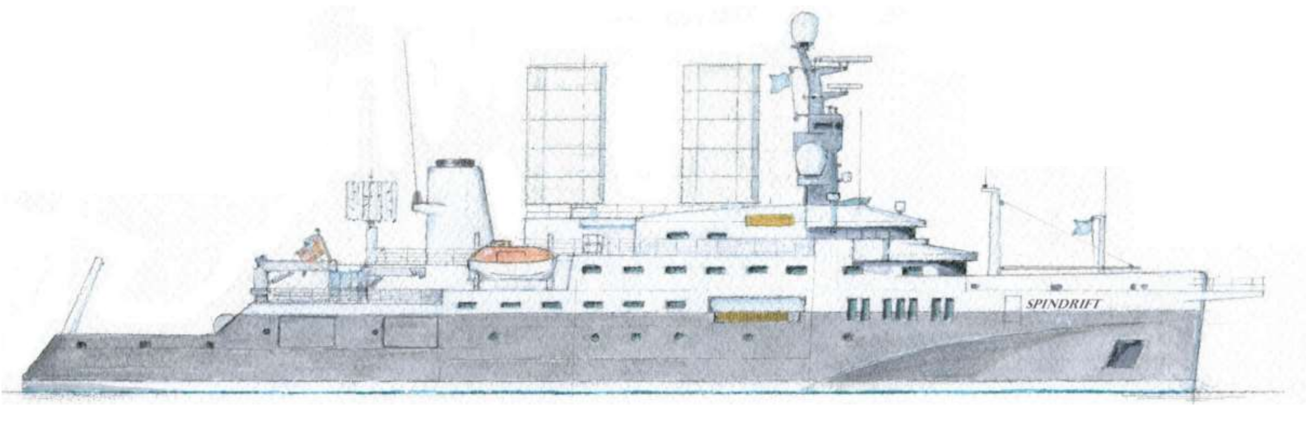


Figure 2.10 Final concept for Extraordinary Innovation Project Spindrift, illustration made by Atle Ellefsen[2]

The Ocean Cleanup

The Ocean Cleanup is a non-profit organization focussed entirely on plastic recovery from the oceans, rivers and waterways. Their aim is to use advanced technology in order to achieve a higher efficiency on a large scale and by an environmentally sound way reducing the amount of plastics in the ocean. The foundation is relying on donations entirely, and is today's biggest independent organization in this field. Their most recent solution is a passive free-floating barrier system of roughly 600 m in length and equipped with a screen reaching four meters below the water surface, see Figure 2.11. Their plans are validated by intense model testing. Based on their findings, it is expected that >95% of plastics of >10 mm can be caught by the barrier. After collection, the plastic will be brought ashore by vessels for recycling. Before scaling this system to a global scale, a first system was deployed in late 2018 in the North Pacific Gyre. Upon achieving successful results, TOC aims to gradually scale up to 60 systems. The long-term goal of TOC is to have cleaned up 90% of the current mass of marine plastic globally (*Technology | The Ocean Cleanup*, 2018).

Compared to other clean-up initiatives, The Ocean Cleanup is probably the largest independent player in the field. Their positivity and aim-for-the-sky approach and strong ownership of the problem are their key elements.

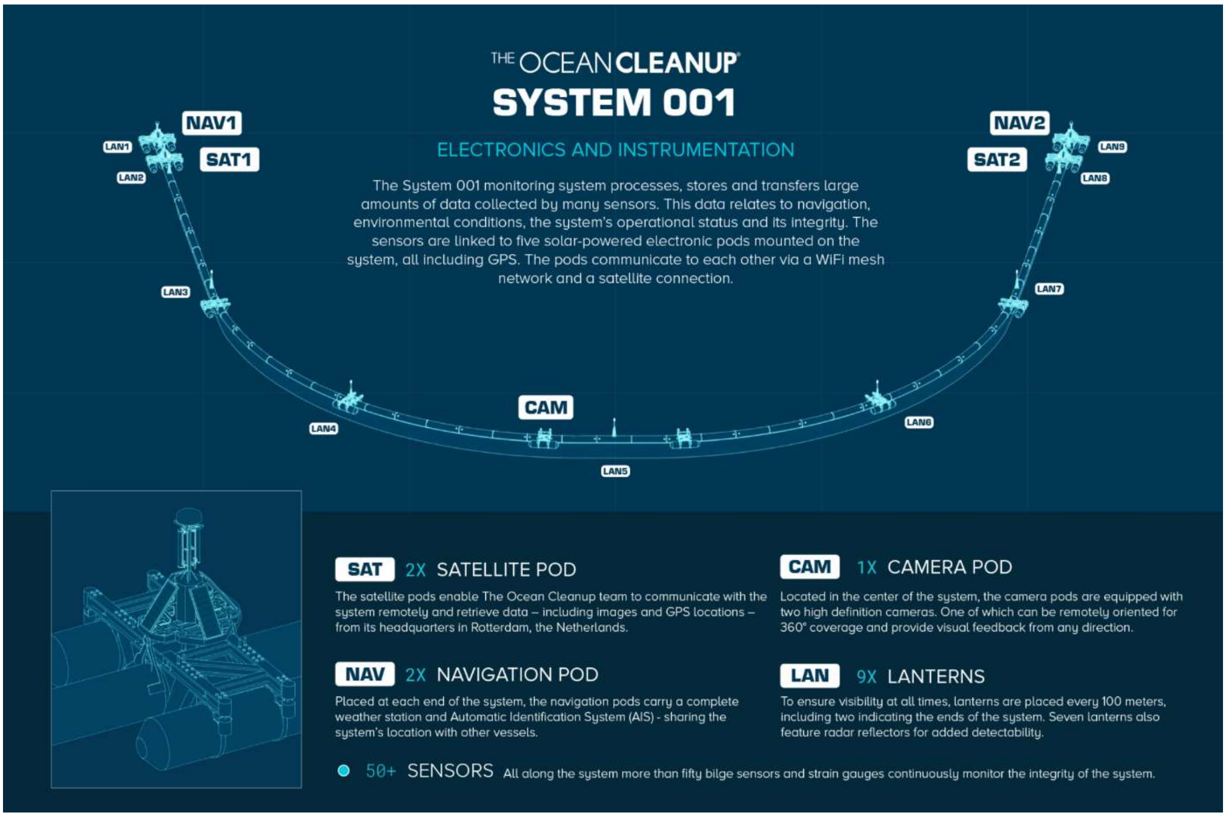


Figure 2.11 One of the concepts of The Ocean Cleanup, image is courtesy of The Ocean Cleanup Foundation

PGS

PGS[3] is currently developing a concept that utilizes their seismic vessels for large scale ocean plastic recovery (PGS, 2018). The concept is in a mature state of design, since it is using their existing technologies. Their solution consists of a seismic vessel and a support vessel towing booms in a fan formation, which are connected to a processing unit at the end of the spread. The seismic vessels are usually used to retrieve seismic data. In this case, the onboard compressors are used to pump air through a ventilated hose, towed at 50 meters water depth. The air bubbles attach to the submerged plastics which then rises to the surface. Then, it can be relatively easily collected by the booms and

[3] Einar Nielsen, Vice-president of PGS, interviewed on April 18, 2018 in Lilleaker, Norway.

sorted by a separating unit at the end of the installation, see Figure 2.12. The system was expected to be deployed in June 2018, but is postponed until further notice.

PGS is an interesting concept because of their motivation to get involved. By launching this concept and technology, they want to expose their willingness to act, their sense of responsibility for ocean restoration and hope to improve other companies to join such an initiative.

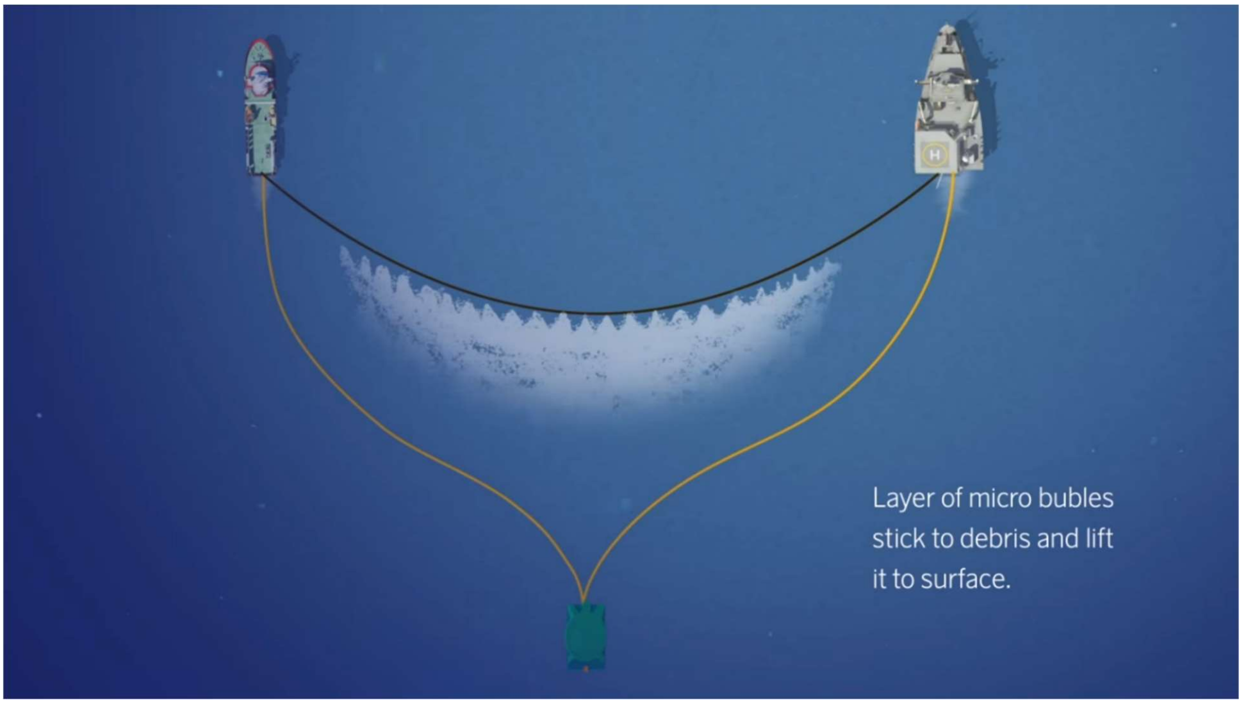


Figure 2.12 PGS concept, image is courtesy of PGS

The World Wildlife Fund and REV

Regarding the plastic waste problem, The World Wildlife Fund (WWF) perspective is based on the statement that "*plastic itself is not the enemy, but the way we handle it is*". Since 2012, they joined the Trash Free Seas Alliance®, a coalition of business, science and conservation leaders dedicated to finding solutions to ocean pollution. Their main focus is at the source – designing strategies to stop plastics from entering the oceans. The alliance already has mobilized many people to remove trash from beaches, but they are looking for more effective solutions for both removal and prevention. Since the scope of this thesis is only looking at removal, the preventive solutions will not be considered too deeply here. For removal they apply the mostly used, but probably the least efficient solution: beach clean-ups. The WWF-Canada has an interesting data log of all the Canadian beach clean-up initiatives, where they show that in only in Canada 1,829 clean-ups have taken place since 2004. In total, they have cleaned 2990 km and recovered 88721 kg of plastic. For this achievement, 58018 volunteers have been involved (The Great Canadian Shoreline Cleanup: Vancouver Aquarium; WWF, 2017). Comparing this to the speed of plastics entering the ocean of roughly 8 million tonnes per year, or 253 kg/s, this comes down that all those volunteers were needed to compensate for a global plastic inflow of only 350 seconds.

Fortunately, in the meantime the Trash Free Seas Alliance®, the Ocean Conservancy and the Closed Loop Partners are launching an initiative to raise over $150 million for a new funding mechanism to prevent plastic waste from leaking into the ocean. The funding mechanism is currently being developed by the Closed Loop Partners, which will also function as an investment firm that "*invests in companies, technology and recycling facilities to turn waste into value and advance the circular economy*". They are aiming for areas around the top 10 polluting rivers, since those are the main contributors to ocean plastic. The funding should emerge technologies to capture and transform waste into valuable commodities, while also providing tangible benefits to communities (Ocean Conservancy, 2017).

Although no further details about this initiative has been published, it could create a fertile foundation for a technology push.

Furthermore, the WWF works closely together with project REV (Research Exploration Vessel). This is a Norwegian custom-build superyacht that dedicated one third of the space on board for the collection and investigation of plastic pollution and reduction.

Figure 2.13 REV Ocean, courtesy of (*REV Ocean*, 2018)

2.4.7 CONCLUSION SUB-QUESTION 3

This paragraph described how leading maritime organizations formulate the current problem statement and rate its importance, and how they describe their future approaches. It can be concluded that there is a discrepancy between the viewpoint of leading maritime organizations and the industry itself. The maritime organizations have many interests to serve, whereas the industry focusses on the development of technologies. However, in order to control the risk, both are necessary. As was assumed in the introduction, any viable plan should have a robust foundation bridging between a technological, financial and social levels. Initiatives such as the Trash Free Seas Alliance® or the approach from the Japanese Government sound promising for that reason, since they include technology by finding ways to recover and recycle, financially by funding and socially by promoting employment and new businesses.

Noteworthy is the fact that the maritime organizations are not directly responsible for developing new technologies, but that their vision and requirements should be nevertheless, well-considered. Organizations as the IMO have the potential of developing new rules, regulations and guidelines that the industry has to obey. The same applies to more governmental organizations that can become responsible for funding and/or monitoring. Based on their vision statements, it can be said that main corresponding values are transparency, scalability and durable recovery and maintenance of the environment.

2.5 DEFINING PARAMETERS FOR THE COST-BENEFIT ANALYSIS

As mentioned in the last conclusion, many different parties are involved in solving this issue, all with many different needs. This chapter combines those different approaches and needs into an overview to determine the most important influencing factors for a successful recovery strategy. Overall, we have seen that technologies are focussed on technical and financial feasibility, whereas the organizations focus on pursuing values as nature recovery and offering a sustainable and transparent solution space for initiatives. In this chapter the most important influencing factors are identified, seen from a strategic and technical perspective. Both the Strategic Solution Space and the Technical Parameters are intended as a theoretical foundation for the methodology for a cost-benefit analysis (Phase 2).

2.5.1 The Strategic Solution Space for ocean plastic recovery

During the research for the risk control options, it was found that many different maritime organizations are led by their vision statements, strategies and goals, desiring for more knowledge and durable and social ways for plastic recovery. On the other hand, the industry itself mainly focusses on technological and financial feasibility. In order to find a solution designed for high impact, all interests should be combined into one strategic solution space. According to the literature study, the strategy intended for the highest impact should involve the factors that are given in Figure 2.14. The purpose of the strategic solution space is mainly to:

- Unite different parties and stakeholders;
- Identify the most important design parameters;
- Connecting direct and indirect influences;
- Unlock value; the sum is greater than its parts. It is believed that just focussing on the short term direct costs and income will not solve the issue, since it created the problem in the first place. There is a great need for benefits and incentives to start acting. These factors are closely related to the more indirect benefits of the strategic solution space.

The Strategic Solution Space is built up by three main qualitative fields, which are environment, technology and society. Interconnection of those three fields creates value which is placed in the middle of Figure 2.14. The labels attached to each field represent the most important design goals or requirements.

For environment the main goals are to restore and conserve the ocean, so that the biodiversity is secured and protected. In order to do so, the human impact should be reduced, meaning that the direct impact humans have on the ocean should be reduced and when doing so, the risk that the polluted oceans bring for humans is being reduced as well.

The labels attached to technology address the main technological design requirements. Since it is a global problem, the solution should be easily scalable, and flexible so it can adjust to plastic concentrations, weather, current and other influencing factors in a dynamic manner. Next to these requirements, it is important that the solution is recovering plastics in a durable and safe way. Ultimately, plastic recovery should lead up to a reduction of the overall risks for an acceptable investment, and should not lead to any increases of risk or disproportionate costs.

The labels attached to society are found to be of great importance regarding the leading organizations, but is often forgotten by the industry (conclusion from paragraph 2.4) . For effective recovery, ownership and responsibility from the society is necessary. Meaning that even though this a cross-border problem, the society should be able to feel responsible and cooperate across borders. This involves leadership from head of states and great involvement from the society itself. A way to do so, is to promote employment and new businesses. Eventually, this will be a great contributor to the added value in connecting the different parts of the triangle.

Next to these factors, the research pointed out that there is a need for transparency. The people involved need confirmation that their efforts are being appreciated and useful, and that they are contributing to the system.

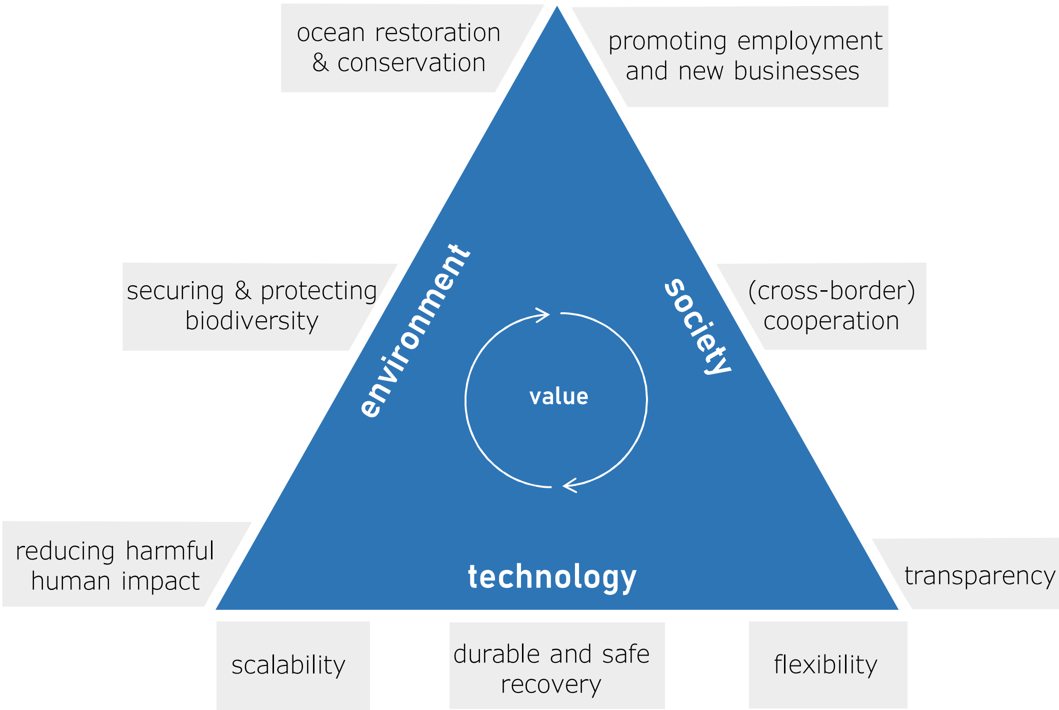


Figure 2.14 Strategic Solution Space for ocean plastic recovery; ©Vera Terlouw

2.5.2 Connection of the Strategic Solution Space to the Sustainable Development Goals

To prove the purpose and relevance of the Strategic Solution Space, the model is connected to the Sustainable Development Goals (SDGs), see Figure 2.15. The SDGs are a collection of 17 global goals set by the UN, covering a broad range of social and economic development issues (United Nations Global Compact, 2016). This figure also demonstrates the potential multilateral benefits, which eventually will help to determine a certain willingness-to-pay for development and implementation of concepts. According to the interviews with Bjørn Haugland[4] and Bente Pretlove[5], pollution of our oceans is one of the main global challenges we face today, but is very closely connected to many industries, societies and economic growth. Taking this into account, the Strategic Solution Space should be directly related to today's global issues and opportunities.

As Figure 2.15 shows, the foundation relies on many more SDGs than SDG 14 (Life Below Water) only (which is placed in the middle of the triangle). Restoration and conservation of the ocean has a direct effect on global nutrition (SDG 2), good health and well-being (SDG 3), clean water (SDG 6) and responsible consumption and production of resources (SDG 12). For the reduction of harmful human impact, we see an even bigger impact, since this factor has the potential to improve education (SDG 4) and can change the way we produce and use energy (SDG 7) and contribute to climate action (SDG 13).

[4] Interview with Bjørn Haugland, Chief Sustainability Officer at DNV GL on June 15, 2018 in Høvik, Norway. The relevance of plastic recovery seen from a global sustainability perspective was discussed during this meeting.
[5] Interview with Bente Pretlove, Programme Director of Ocean Space, Oil&Gas and Energy Systems at DNV GL on June 18, 2018 in Høvik, Norway. The development and the possible implementation of the Strategic Solution Space was discussed during this meeting.

Seen from a technology perspective, the scalability and safety of the operations can potentially help to improve the industry, innovation and infrastructure (SDG 9) and create sustainable communities (SDG 11). The strongest connection to the SDGs can be found in the societal part of the Strategic Solution Space. Implementing plastic recovery solutions will promote employment and new ventures, which will contribute to many SDGs such as no poverty (SDG 1), education, decent work and economic growth (SDG 8) and strong institutions (SDG 16). Cooperation will also promote equality (SDGs 5 and 10), and create a better working environment for life on land (SDG 15).

This step was closely connected to the DNV GL specific recommendation that was developed during this thesis (paragraph 8.3.2).

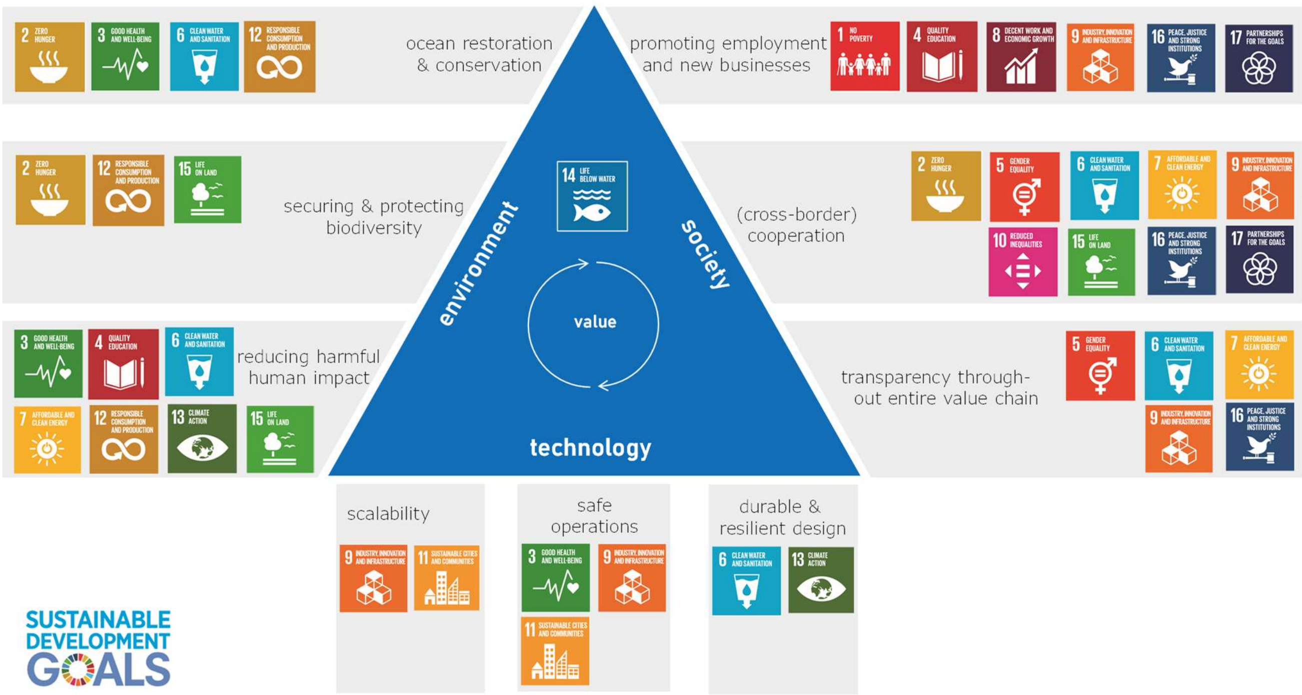


Figure 2.15 Second iteration of qualitative factors in ocean plastic recovery, © Vera Terlouw

2.5.3 The Technical Parameters

The to be developed methodology is based on the comparison of different solutions. In order to compare, quantification of the most important technical parameters can play a big role. This paragraph makes a preliminary step towards the quantitative comparison of technologies, also based on the findings of the literature study.

The financial feasibility of a technology is dependent on the operational and investment costs, well balanced against income. The driver for income could come directly from the plastics that the technology can recover, but it could also come from funding. It is very likely that this funding is related to the Recovery Potential – an estimated recovery rate combined with the area. The following list contains the parameters, including a unit to allow quantification:

- OPEX: operational expenses [USD]/[time];
- CAPEX: investment costs [USD];
- Recovery Potential: estimated recovery rate combined with the recovery area [tonnes]/[time].

These technical factors will be further assessed in both the first and the last part of the methodology. The middle part will have a more strategic approach based on the findings and implementation of the Strategic Solution Space.

2.5.4 CONCLUSION SUB-QUESTION 4

This paragraph discussed what kind of parameters may be considered during a cost-benefit analysis. The literature study pointed out that many influences are not directly describable in numbers, but could be considered by a more qualitative approach. The cost-benefit analysis will be split up in two parts:

- A qualitative approach by the Strategic Solution Space
- A quantitative approach by Technical Parameters

The qualitative part has the ability to focus on the entire-value chain of concepts, considering the benefits for society, environment and technology. The literature study unveiled the importance of uniting stakeholders (organizations, industry and the society) in order to obtain feasible solutions. Furthermore, it is of great importance to look further than just the direct cost and income, since the imbalance between cost and income was right at the origin of ocean pollution. Benefits such as ocean restoration and conservation should be considered and valued in development and assessment of recovery solutions.

The technical part is aimed to quantify parameters that will have a significant influence on the feasibility of the to be assessed technology. The most important technical parameters are:

- OPEX: operational expenses [USD]/[time]
- CAPEX: investment costs [USD]
- Recovery Potential: estimated recovery rate in combined with the recovery area [tonnes]/[time]

PHASE 1/3 CONCLUSIONS & RECOMMENDATIONS

The research goal was to investigate the state-of-the-art of plastic waste recovery to find which main design parameters can be identified in order to develop a methodology quantifying the feasibility and effectiveness of plastic recovery solutions from oceans, rivers and waterways.

The state-of-the-art can be defined by a combination of hazard identification, risk assessment and control. Assessing different scenarios show that implementing barriers (both proactive and reactive) can have a positive impact on the reduction of risk. If nothing would happen at all, if no barriers would be put into place, the amount of plastic reaching the ocean will continue to build up. Today's estimation is that over 250 million tonnes will be adding up in the 5 ocean gyres, (Jambeck *et al.*, 2015). Consequences of not acting are more than just pollution. The plastics break down under chemical (UV, hydrolysis, oxidation) and mechanical (abrasion, wear, tear) into micro-plastics, and entering the food web via ingestion. Apart from that, plastics are known to have the ability to adsorb hydrophobic pollutants. This means that in case of ingestion, next to blockage and starvation, toxicity is another concern the animals, and humans are put up with. Also the macro-plastics are a direct hazard for humans, by blockage and breakdown of equipment.

ADDED VALUE: As was established by the bow-tie model, preventive barriers could stop plastics from entering the oceans. However, a lot of changes need to be made in order to do so. The majority of ocean plastics is originating from East-Asia, where the main reason is the absence of a waste infrastructure that meets the requirements of a quickly growing economy, (Isobe *et al.*, 2015). In the meantime, reactive barriers can play a huge role in preventing the worst consequences from happening. Recovery of plastics (which is a reactive barrier) could have the great advantage of adding a (monetary) value to the system of reducing plastic waste, and create a great momentum for the transition towards a circular economy.

ADDED VALUE: To come back to the research goal, the parameters for feasible and effective design are subjected to many direct and indirect influences. The study showed that next to leading maritime organizations, the maritime industry itself could play an important role in plastic recovery. By creating a certain benefit for recovering plastics, the sense of responsibility and ownership of the shipping industry could increase and start to have an impact. In order to create this sense, some kind of willingness-to-pay must be investigated. Therefore, a strong strategy has to be in place to connect on technological, environmental and societal level, resulting in the Strategic Solution Space. Furthermore, the main parameters in order to quantify effectiveness and feasibility are the OPEX, CAPEX, and recovery potential.

The Strategic Solution Space and the Technical Parameters are the starting point of Phase 2: the development of a methodology assessing the feasibility and effectiveness of solutions for ocean plastic recovery.

PHASE 2/3

During this second phase, the parameters from Phase 1 are used to develop a methodology to systematically assess the cost, benefits and effectiveness of solutions. The goal of developing this methodology is to provide a design support for those who want to assess how effective and resource demanding a given solution will be, and which conditions should be in place to ensure the solution will work as intended.

The goal is to compare solutions, but also to compare the solutions to the case where no one acts at all, which is called a business-as-usual scenario. Therefore this phase starts with a recommendation for a trajectory study which allows measures to be compared to a certain baseline. Trajectory studies are a common approach for anthropogenic problems[6], but have not been applied to this particular problem yet. However, when comparing concepts it is essential to understand its overall impact, which can easily be measured by such studies. Chapter 3 will describe how a trajectory study can be developed for plastic pollution of the oceans, and what kind of research questions need to be answered.

After this, the methodology builds up in several steps, allowing to start with a high-level screening, and eventually zooming in on the most favourable concepts for a detailed cost-benefit analysis. This is a result of the obtained conclusion of Phase 1, where it was found that we should look further than just the direct cost and income. The steps of the methodology are:

1. Technology screening: this step collects technologies that are currently developed for plastic recovery or similar purposes. After collection, the technologies will be organized based on a first estimation of cost and recovery potential. Then, the most promising applications of technologies will be selected for the next step.
2. Qualitative judgement: the Strategic Solution Space (Figure 2.14) will be used as a starting point for development of criteria for a qualitative comparison of concepts. As previously found, these qualitative criteria are closely related to personal engagement on both business and societal level, and are therefore so important to consider. The two concepts with the strongest strategies will be selected for the last step of the methodology.
3. Cost-analysis of two case studies: The two favourable concepts are closely investigated, estimating its investment, operational and voyage cost, and compared with its estimated impact, or benefit. This impact will be an estimation of the total recovered ocean plastic per year for each of the concepts.

ADDED VALUE: Ultimately, these three steps will provide more insight into the feasibility and effectiveness of recovery concepts. Of course, the three steps allow iterations to improve matters effectively.

[6] Anthropogenic problems: negative influences from human beings on nature

3 DEVELOPMENT OF THE METHODOLOGY

In the research field of ocean pollution, the future has scarcely been explored. As previously found in the literature research, the most advanced forecasting is based on extrapolation of the worst consequences. Today, it is simply assumed that the worst consequences will occur at a higher frequency, and that assumption is supposed to serve as sufficient motivation to reduce plastic pollution. However, it is possible to forecast in a more reliable and scientific way, which emphasizes the impact of effective solutions over a longer period of time. This chapter will make a first step towards a more sophisticated approach on forecasting by looking at different trajectories (or mitigation pathways) for plastic pollution. Seen the scope of this thesis, the emphasis will be on ocean-based mitigation strategies.

3.1 THE FIRST OCEAN PLASTIC RECOVERY TRAJECTORY

Trajectory studies show different pathways over time. The different pathways are comparable, but are subjected to individual influences and efforts, and come at different costs. The advantage of using a trajectory-based study is, is that the solutions are not only compared to each other, but also compared to the situation where no one acts at all. This situation is called a baseline and represents the business-as-usual scenario, also discussed in paragraph 2.3.1. This baseline functions as a reference line for the other trajectories and is essential to define the gap, or a reduction of a certain outcome, over time. The other trajectories are dependent on reduction measures that eventually lead to a different outcome. The direction is usually dependent on the availability of effective measures and the willingness to implement these measures, which is subsequently dependent on strategic variables such as available investment funds, awareness, or (the absence of) rules and regulations or pressure from society.

The use of trajectories is particularly interesting for plastic reaching the ocean, because it involves a status-quo and business-as-usual forecast. Such a study may also result in many research recommendations, which will help us to create better understanding and will help us to develop the most effective concepts.

3.1.1 Trajectories in other fields

This method has been previously used for upcoming markets that related to anthropogenic issues[7]. An interesting application of trajectories is for greenhouse gas (GHG) emission reduction targets for international shipping. DNV GL carried out a study to identify the operational and economic consequences from existing and proposed future CO_2 regulations (Stern, 2017). In order to do so, they explored and analysed CO_2 trajectories to meet a 2-degree emission towards 2100 for international shipping, as discussed in the Paris Agreement (UNFCCC, 2015). The studied measures outline robust strategies to meet the requirements. The trajectory study executed by DNV GL functions as a strong connection between measures, requirements and investments.

A basis for global action for land-based strategies to reduce the plastic pollution was provided by (McKinsey Center and Ocean Conservancy, 2015). They have used a similar approach, for a similar problem, because the method is underpinned by a strong understanding of possible solutions and their economics. The set of measures have a calculated impact, a potential reduction of waste leakage, for a certain investment cost. Trajectory studies usually function as a connecting mechanism involving the public, private and multilateral sectors. The reason is that the measures tend to come from private initiatives, but the investments have significant returns to the entire economy. Overall, the trajectory studies have shown to offer a strong and broad foundation for investigation of new markets related to environmental issues. It has the potential to connect the different factors as previously found in the literature study and to quantify the investment and benefits of the recovery measures.

[7] According to Øyvind Endresen, environmental specialist at DNV GL, interviewed on April 19, 2018 in Høvik, Norway.

3.1.2 Development of the first ocean plastic recovery trajectory

The first step towards trajectory is to approach the ocean as black box, or a source-sink model, and identify the main in- and outputs, see Figure 3.1. These in- and outputs represent the most important components of the trajectory equation. This is a first identification of in- and outputs and need to be substantiated by scientific research. For this reason, the source-sink model is applied on a high-level analysis, where the black box represents an entire ocean. When more detailed knowledge is gathered, the analysis can look into a smaller, but more in-depth black box, such as a specific region of an ocean, river or waterway. For now, the source-sink model is approached as generic as possible, and can be used as a robust starting point for further research.

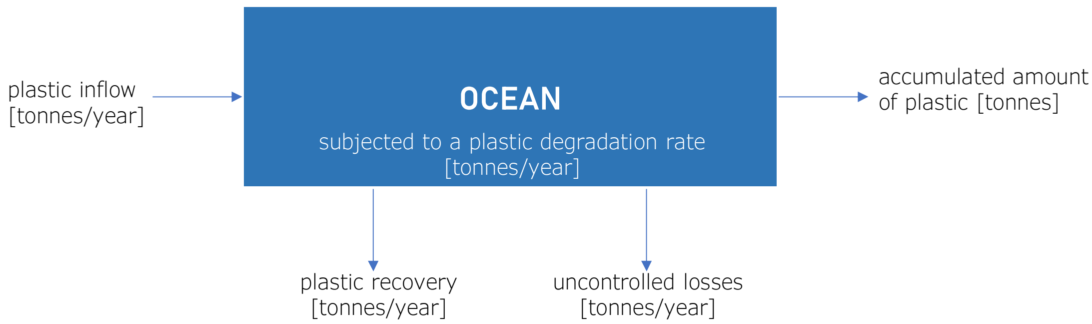


Figure 3.1 Source-sink model for parameter overview for future trajectories, ©Vera Terlouw

Based on the literature study, the main in- and outputs related to the black box are p_{in} as *plastics inflow [tonnes/year]*, p_{rec} as *plastic recovery [tonnes/year]*, and p_{loss} as *uncontrolled losses [tonnes/year]*. This number is subjected to p_{d} as the *degradation rate [tonnes/year]*. The total sum leads up to the $p(t)$ as the *total accumulated amount of plastic* in the ocean as a function of time. These parameters can be combined into an equation[8], which is applicable to every point along a trajectory:

$$p(t) = p_{in} + p_{loss} + p_{\mathrm{d}} + p_{rec} \qquad \textit{Eq. 3.1}$$

As for many source-sink models, it should be taken into account that some of these variables have a negative influence, such as the losses and degradation rates. All the parts of the equation are flow-dependent, which allows us to translate the equation into a first-order differential equation:

$$\dot{p}(t) = \frac{\partial p(t)}{dt} = \dot{p}_{in} + \dot{p}_{loss} + \dot{p}_{\mathrm{d}} + \dot{p}_{rec} \qquad \textit{Eq. 3.2}$$

And the separate parts can be described as:

$$\begin{aligned} \dot{p}_{in}(t) &= \frac{d\dot{p}_{tot}(t)}{dt} \\ p_{loss}(t) &= L \cdot p(t) \\ p_{d}(t) &= D(x,y,z,t) \cdot p(t) \\ p_{rec}(t) &= R(x,y,z,t) \cdot p(t) \end{aligned} \qquad \textit{Eq. 3.3}$$

Where the derivative inflow over a period of time equals the derivative of the total amount of plastic over the same time interval. The total losses are dependent on a loss function (recommended research),

[8] This source-sink equation was developed together with Jiri de Vos, BSc. on April 26, 2018 in Delft, The Netherlands.

and the degradation as a degradation function as a function of location (x,y), depth (z), and time (t). For the degradation rate in particular, Jon Huse[9] pointed out that the long-term degradation of plastics is still largely uncertain. Many factors (size, distribution, weather, UV, waves, etc.) are involved in determining the degradation and is therefore not that straight-forward to determine. However, a recommended starting point for further research is to approach it from a strength-perspective. For a lot of polymers, it is known when the material has lost 50% of its original strength. This can be extrapolated to a 100% loss. Then, it can be assumed that the polymer is not strong enough to maintain its internal links and will break down into smaller parts, eventually breaking down to monomers; the polymers building blocks. Those monomers could be less harmful, since the molecules are much smaller and weaker. Connection to toxic materials is therefore also less likely. However, it should be mentioned that a monomer still is a chemical structure and need further investigation on these statements. All those factors have an influence on the plastic recovery p_{rec} as well. None of these functions have been investigated thoroughly, but leads to many new topics for further research. Of course, the plastic recovery p_{rec} will be further investigated during the development of this methodology.

Figure 3.2 shows an illustration of a possible trajectory for the business-as-usual (which is the baseline), and a trajectory when plastic is recovered. The gap between the two trajectories represents a space that sets the need for measures. In relation to this thesis, there is a great need for finding the most effective measures that will eventually help to decrease the accumulated amount of ocean plastic $p(t)$. The illustrated recovery-trajectory is one of the many possibilities it could go; each measure could have an influence on the parameters mentioned above. The effectiveness of each measure is dependent on the extent to which it is meeting the criteria. The measures and criteria will be further discussed in paragraph 5.1.

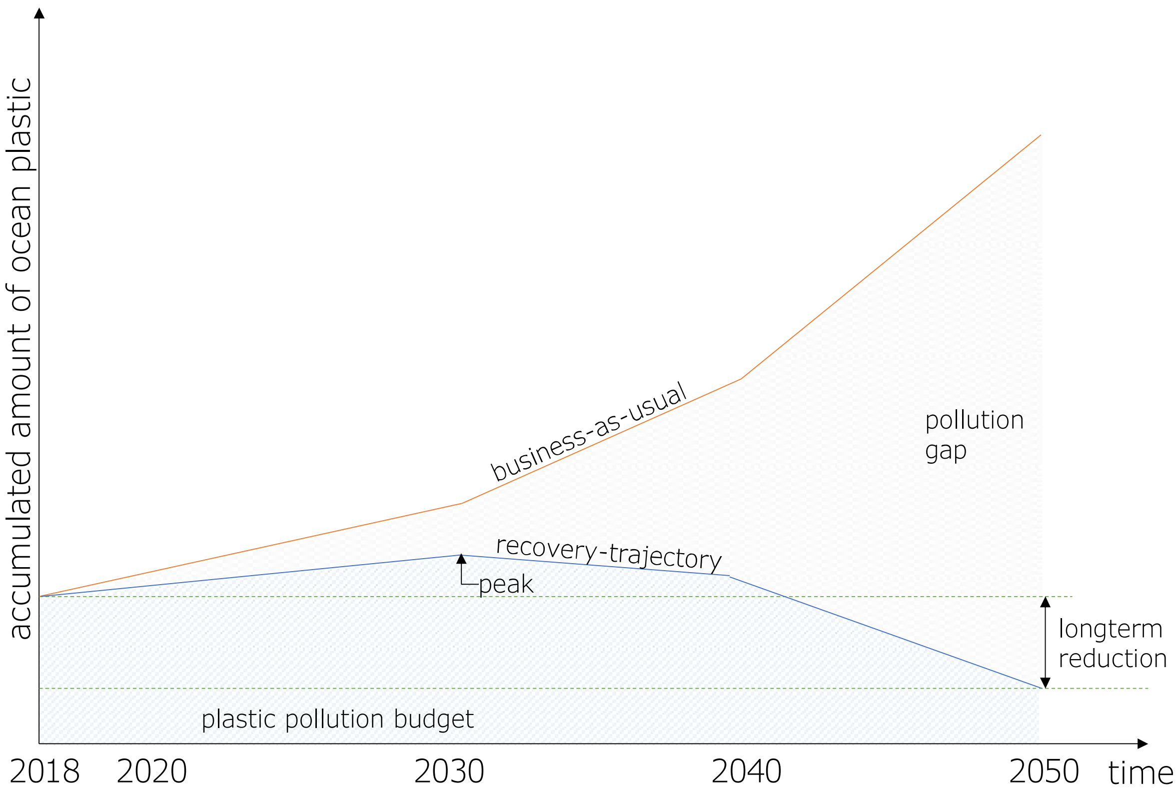


Figure 3.2 Trajectory for accumulated amount of plastic in the ocean, inspired on (Mjelde *et al.*, 2014), *©Vera Terlouw*

[9] Jon Huse is a polymer material specialist at DNV GL, interviewed on April 12, 2018 in Høvik, Norway.

3.2 THE METHODOLOGY'S STRATEGY

The aim of the methodology is to quantify and assess the effectiveness and feasibility of concepts for plastic recovery p_{rec}. This paragraph describes the necessary steps that need to be taken and can be seen as the overall strategy for Phase 2. The figures here are illustrations only and are not yet connected to actual data. This will happen in the following chapters when the steps are executed.

The strategy is based on several anthropogenic methodologies that were encountered during the literature study. In the past, many different approaches have been used to analyse costs and benefits of technologies to solve environmental issues. However, the most interesting ones (paragraph 3.1.1), all have a clean and understandable approach, clear assumptions and stepwise assessment of the technologies. The strength of those methodologies is that they all use a multilateral approach, and by doing so offering a good balance between the most important parameters.

Figure 3.3 visually describes the process of the methodology, starting on the far left and progressing towards the right. Three main steps are established, which are technology screening, qualitative judgement and eventually the cost analysis. The large shapes in the figure illustrate the methodology stages, this can either be diverging, analysing and converging. In a stage of divergence, the concepts will be collected, and thus increase in numbers. During analysis, the number of concepts remain the same, but will be organised by applying criteria. In a stage of convergence, the most favourable concepts are selected, so the total number will be reduced. The smaller shapes (the triangle, circle, square and pentagon) represent different types of recovery concepts. During the process the concepts will be analysed and selected in a step-wise manner. The details of the three steps are separately discussed on the next page.

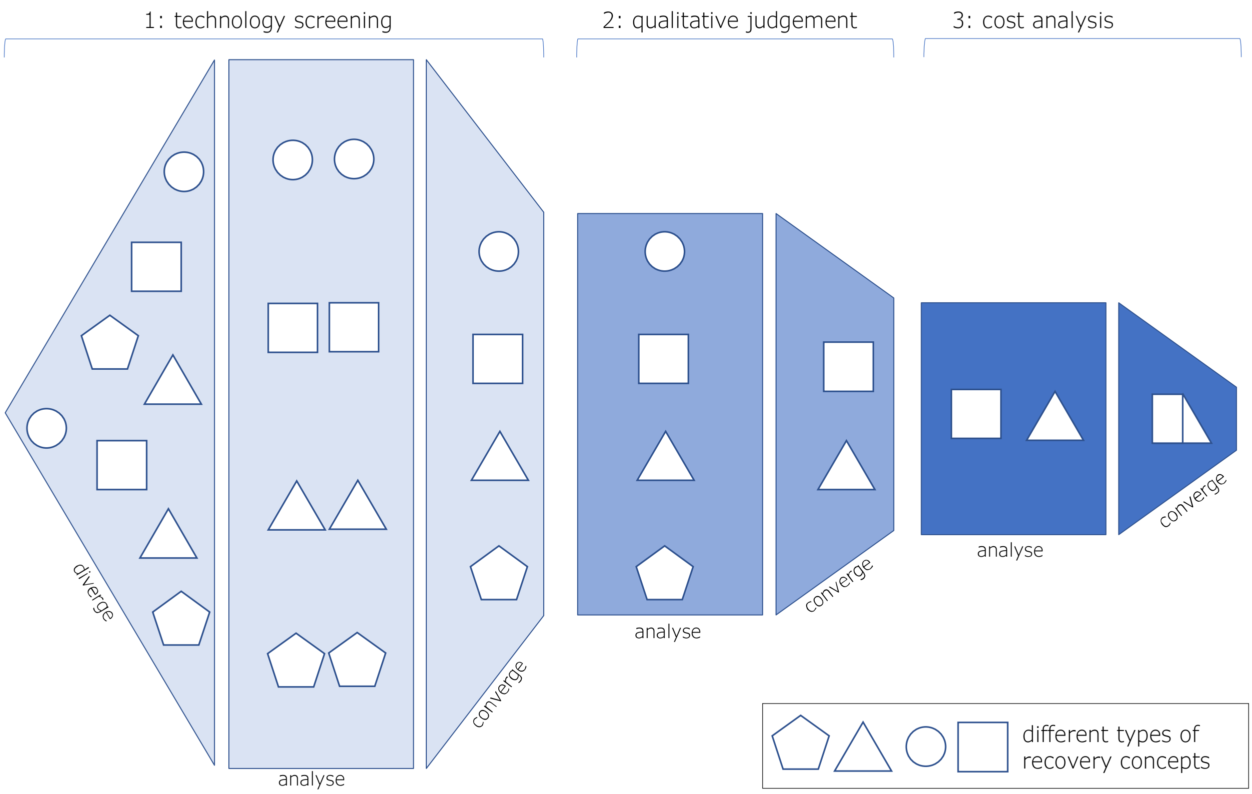


Figure 3.3 Process description for methodology, with 3 main steps for a technology screen, qualitative judgement and a cost analysis, ©Vera Terlouw

3.2.1 Technology screening

- Diverge: Collect all technologies that are currently used, being developed or could be used for ocean plastic recovery. This can be done by online searches, creative sessions and interviews.
- Analyse: Estimate the operational cost and recovery potential and organise technologies into concept groups. This is a first rough estimate and is based on the accessible information of each concept.
- Converge: Select the best concepts based on maturity and first impression of feasibility.

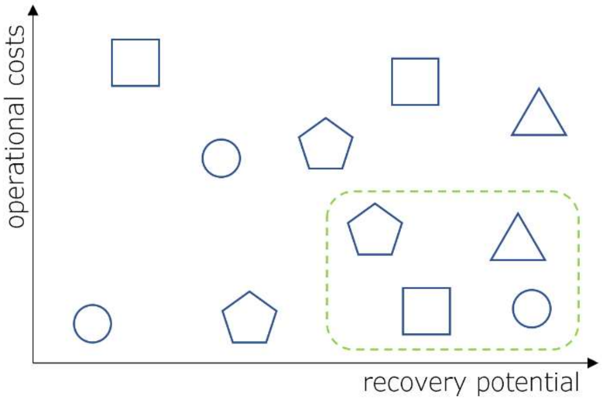


Figure 3.4 Methodology step 1: Technology screening

3.2.2 Qualitative judgement

- Analyse: definition of qualitative criteria based on the Strategic Solution Space (paragraph 2.5.1), considering qualitative criteria for technological, environmental and societal impact. The weight of each criterion must be based on input from multiple experts. Judgement of the concepts is structured by a well-defined scale, and based on input from a representative group of stakeholders.
- Converge: Select the most favourable concepts based on highest ranking.

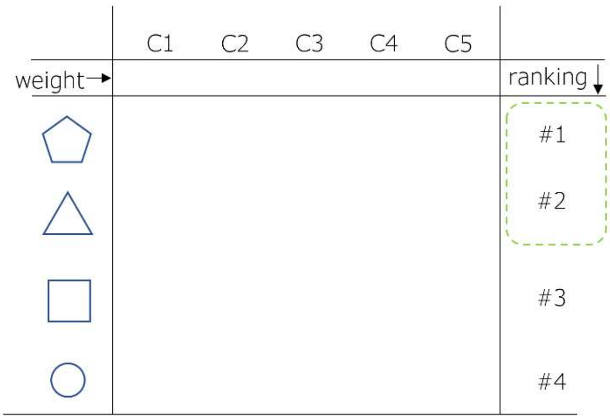


Figure 3.5 Methodology step 2: Qualitative judgement

3.2.3 Cost-analysis: Case Studies

- Analyse: Detailed cost estimation of the two most favourable concepts. The cost is based on the investment, operational and voyage cost. This part of the methodology also includes a new estimation of recovery potential.
- Converge: Selection or combination of best aspects of concepts, based on both the total cost of operation, the estimated cost per recovered tonnes of ocean plastic, and the total impact.

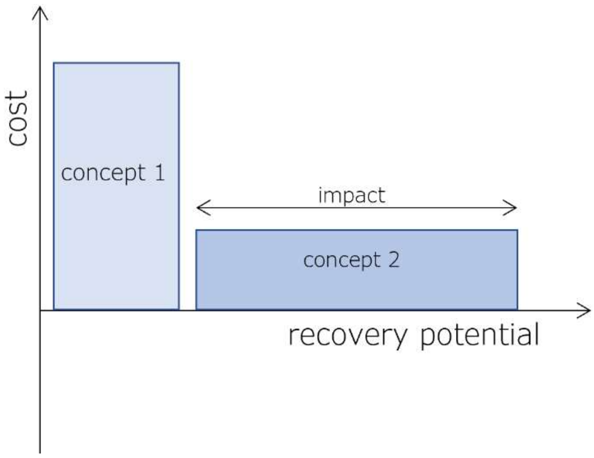
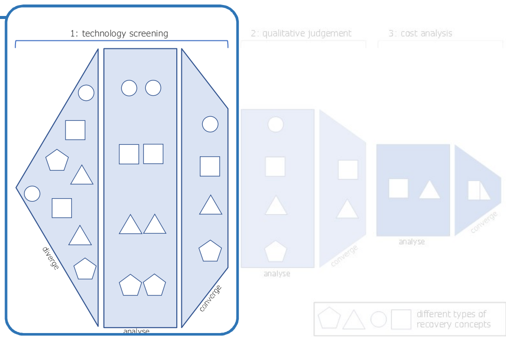


Figure 3.6 Methodology step 3: Cost-benefit

Altogether, the methodology will function as multilateral design support tool suitable for a large collection of concepts, where the degree of detail is increased by every step. Noteworthy is that the feasibility and effectiveness that were mentioned in the goal of this thesis are not used as direct parameters in any step of the analysis; the aim of the methodology is to find concepts with the highest feasibility and effectiveness, which is done by successively analysing all contributing parameters. Furthermore, it should be mentioned that the most favourable concept is not necessarily the best one; it is likely that many design recommendations are found during the analysis. Then, the concept can be further optimized by a second iteration through this methodology.

4 TECHNOLOGY SCREENING

This chapter describes the first step of the development and application of the methodology. As described in the previous chapter, this step will function as a first screening and filtering of technologies. To do so, technologies should be collected and assessed. Then, the most feasible ones will be used for further analysis. The focus of this step is on the technologies, including all technologies that are currently used, being developed or potentially could be used.



ADDED VALUE: This part of the methodology offers an impartial collection and assessment of the state-of-the-art plastic recovery solutions.

4.1 DIVERGE: COLLECTING TECHNOLOGIES

The database is an overview of today's state-of-the-art of technologies for ocean plastic recovery. The aim is to execute a high-level screening of all plausible technologies, then organize them by concept type and eventually selecting the best concepts for further analysis. In this collection only the recovery technologies itself are considered; the rest of the value-chain such as market integration is not considered yet. This paragraph describes which technologies can be included, which ones are excluded and what the criteria will be for the first step of the methodology.

4.1.1 Redefining the scope

The technologies need to address a similar goal for a successful comparison. Therefore, the project scope has been slightly refined. Referring to paragraph 1.1, the scope assesses solutions for plastic recovery in oceans, rivers and waterways. The areas along the value chain appeared to be quite diverse when considering the entire water-based solution space. Possible areas for technical opportunities are:

- Collection of waste;
- Conversion/Treatment;
- Recycling;
- And mitigation;

For all oceans, rivers and waterways.

The methodology must be applicable to all of these technical opportunities. Logically, a main requirement for this methodology is that it should be easily applicable to other scopes of anthropogenic problems. For now, the methodology will focus on one technical opportunity area in particular. The scope is narrowed down and now includes:

- Collection of ocean plastic waste that is
    - Floating;
    - In the water column;
    - In sediments.

As previously found in the literature study, the estimated percentage of floating plastics is 0.21% of the total amount. Another 8.16% is estimated to be in the water column. The vast majority can be found in the sediments (91.61%). Luckily, the estimated amount of plastics that is adsorbed in biomass is the smallest number, $3 \cdot 10^{-7}$ %. Although the plastics that can be found in the water column and floating are still a minority, they are likely cause the greatest harm (see paragraph 2.2).

Although the majority of plastics can be found in the sediments, recovery operations are uninviting. A reason for this is that recovery operations of plastic sediments are extremely expensive and inefficient.

According to Jens Laugesen[10], removal of sediments requires in-situ solutions on possibly, great depths, which rely on thorough research. Since there currently is a great lack of plastic sediment research, this will even be more costly. However, it is known that the plastics breakdown and most of them will eventually end up as sediments. As mentioned in paragraph 3.1.2, further research needs to define a baseline and when the conditions would be unacceptable. In short, recovery of plastic sediments is currently not feasible due to lack of research, and is in the current status-quo not an effective measure to take, since it would cover a small area with no guarantee for successful recovery at extremely high costs. For these reasons, the sediments will be not taken into further consideration during this analysis. It is recommended for further research is to investigate the influence of plastic sediments on biodata to improve the feasibility and effectiveness of plastic sediment recovery.

4.1.2 Collecting technologies

The to be included technologies should match with the characteristics of the refined scope. This means that any technology that picks up ocean plastic that is floating or in the water column, can be part of the collection. All other technologies (land-based for example), are excluded. The search was mostly executed online. However, there are technologies from other industries that can be applied to this industry and are also in a mature stage of development. These options were initially investigated by a creative session in Delft.

The online investigation was focused on direct technologies for ocean plastic recovery. Important search words were (combinations possible): ocean plastic, plastic recovery, plastic clean-up, solutions for micro-plastics, marine litter, marine waste, removal technology, ocean clean-up, mitigation strategies, ghost nets, (lost) fishing gear, ocean pollution reduction, sustainable ocean/sea initiatives.

The creative session was held with five people educated in marine technology, ship design and operations, and offshore technology[11]. During this session it was discussed how ocean plastics could be recovered by using technologies from other field such as oil recovery. After collecting ideas, the technologies were organized into several divisions, which also helped organizing the database later on. The first division in types were dynamic/passive solutions, where dynamic technologies have a certain propulsion system and can target a specific area. Passive technologies do not have any propulsion system and are fixed to one location, or freely float around. During this session, different types of technologies were discussed and used as a preceding step before organizing concepts (further discussed in analysing step).

Another source of inspiration was attendance at the Opening Oceans Conference[12]. One of the main findings here was that many offshore companies are ready to invest in recovery of the oceans, since they became aware of the fact that before sustainable utilization of the oceans, the ocean needs to recover first and any further pollution should be avoided. These companies are working on inhouse solutions (PGS, Wärtsilä, Allseas) and/or strongly support external parties and accelerate start-ups. Although most of these technologies are not yet ready to include in the database, they should be taken into account when they have achieved a higher level of maturity. A technology that is included in the database is the air bubble curtain by PGS.

[10] Jens Laugesen is an expert in contaminated sediments at DNV GL, interviewed on April 20, 2018 in Høvik, Norway.

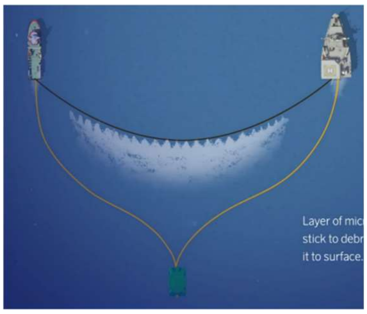
[11] Participants of creative session: Esther Wachter, Julius Jansen, Maurice Mooren, Joris Rusman and was held on May 8, 2018 in Delft, The Netherlands. To structure the meeting, the creative session was split up into separate questions, focussed on recovery technologies, surveying large ocean areas, high precision surveys, recovery considering minimal harm to biodata, recovery with highest safety measures, and recovery with minimal emission of heavy fuels.

[12] Opening Oceans Conference in Copenhagen on the 2nd and 3rd of May 2018 where maritime companies got together to discuss sustainable utilization of the oceans.

When a technology was found, all its accessible data was put into a spreadsheet and briefly described below. Obviously, there was a large diversity in the accessibility of data. However, the most important factors to be identified were a first indication of recovery potential and a first indication of costs. This is further discussed in the analysis (next paragraph). Each of the concepts below have an estimation of operational cost per annum (cost), estimation of recovery potential per annum (RP) and are organized by a certain technology type (TT). The origin of the numbers and technology types will be further explained in paragraph 4.2. This is brief overview of the found concepts and technologies:

PGS

Large onboard processors are used to pump air through a ventilated hose between the seismic vessel (owned by PGS) and the support vessel. The air bubbles attach to the submerged plastic when then rises to the surface. A processing unit at the end of the collection spread separates organic materials from plastic. The plastic is then compressed and packed.
TT: bubble curtain, RP: 980 t/year, cost: 8 million [USD/year]

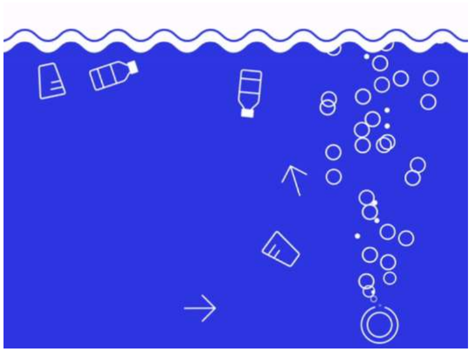


Floating Horizon

A robotic vessel for particle sampling to e.g. monitor marine litter in the oceans. The main parts are the floating skimmer, which is attached to a bunker. The skimmer is attached to a submerged kite (below the surface) which provides the movement of the system. An external service boat collects the collected waste every three weeks. Solar panels on the bunker produce energy for navigation and communication.
TT: boom, RP: 18 t/year, cost: 3300 [USD/year]

The Great Bubble Barrier

A bubble screen by pumping air through a tube with holes located on the bottom of the waterway, creating a bubble curtain from the bottom of the river up to the surface. This upward flow of the bubble barrier brings waste to the surface. *"When placed diagonally, the natural current is used to guide the plastic on the riverside, which makes it accessible for collection and accessible removal."*
TT: bubble curtain , RP: 12 [t/year], cost:3300 [USD/year]

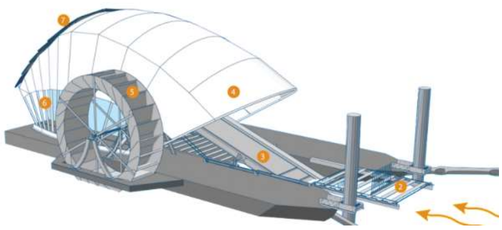


Seabin

The Seabin is a floating rubbish bin that is located in the water at marinas, docks, yacht clubs and commercial ports. The Seabin moves up and down with the range of tide collecting all floating rubbish. Water is actively sucked in from the surface and passes through a catch bag inside the Seabin. A submersible water pump displaces water and pumps it back into the marina leaving litter and debris trapped in the catch bag to be collected and disposed.
TT: pump+filter, RP:0.3 [t/year], cost: 3300 [USD/year]

4Ocean

4Ocean is a global movement actively removing trash from the ocean and coastlines by employing captains and cleanup crews from all over the world. They own a large fleet of small vessels designated for this job that are equipped with nets, hooks and trawls. Each vessel has its own captain and two crew members that manually pick up the marine litter. *TT: trawling, RP: 29 [t/year], cost: 111000 [USD/year]*

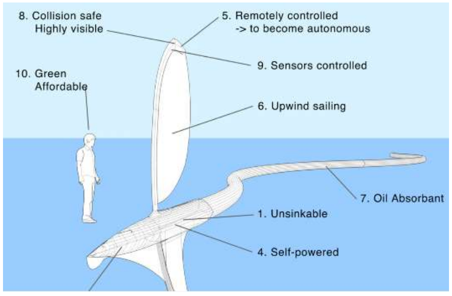


The Inner Harbour Wheel / "Mr Trash Wheel"

The Inner Harbour Wheel (Baltimore, USA) uses the river's current to provide power to turn the water wheel, which lifts trash and debris from the water and deposits it into a dumper barge. When the current does not suffice, solar power can be used as an additional power input. After the dumpster is filled up, it is towed away and replaced. This design is one-of-a-kind and is a project of Waterfront Partnership of Baltimore. *TT: pump+filter, RP: 1.5 [t/year], cost: 17000 [USD/year]*

Protei & Scoutbots

Protei is an open-source hardware shape-shifting sailing robot with the goal to deploy a fleet of renewable-energy powered ocean satellites to collect ocean data. Scoutbots develop the software and develop many concepts and prototypes all with the aim to tackle plastic pollution, oil spills, radioactive leaks, chemicals etc.
TT: boom, RP: 1.5 [t/year], cost: 3300 [USD/year]



Recycled Park

Recycled park is the proposal to retrieve plastic waste from a local river in Rotterdam, Netherlands, before it reaches the North Sea. It is a floating park that is built up from floating hexagon-shaped building blocks, that work together as passive litter traps and offer additional recreational space in city-environments.
TT: filter, RP: 0.01 [t/year], cost: 3300 [USD/y]

Sea Cleaning Drones

Designer Hsu Sean designed an autonomous solution that incorporates a variety of pollution fighting tools (bio-degradating bacteria and acoustic alarms). The system uses biosensor technology to track the flow of the polluting material, thereby streamlining the cleanup process and preventing further leakage.
TT: drone, RP: 0.8 [t/year], cost: 3300 [USD/year]

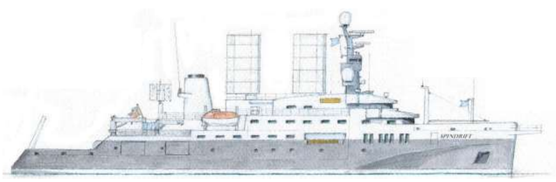
Trawlshare

Trawlshare is a foundation that provide trawls and protocols for citizen scientists to collect data on marine plastic pollution. The trawls are specifically designed for plastic recovery and can be installed on many small boats. The discovered data has to be shared to a global database collecting Trawlsharing data.
TT: trawling, RP: 29 [t/year], cost: 80000 [USD/y]

DNV GL Innovation Project Spindrift

The Spindrift project is a concept for plastic recovery and research. They use a combination of technologies: manta/neuston net (a net that is towed on the side of the ship) and a boom (similar to oil recovery booms). They rely on smart data collection by using drifters, towfishes (an optical counting method that characterizes the density of plankton), AUVs and ROVs.

TT: expedition, RP: 98 [t/year], cost: 760000 [USD/year]



REV Ocean

REV is a privately owned research and expedition vessel, equipped with advanced plastic recovery equipment. On-board they have technology that maps plastic sediments on the sea bottom, many water sampling to measure micro-plastic concentrations (by trawling and water samples) and monitor health of sea life.

TT: expedition, RP: 98 [t/year], cost: 840000 [USD/year]

Rozalia x Parley

Rozalia and Parley have a partnership that organizes expeditions for plastic recovery. The technology they use is called Hector the Collector and is a video-ray pro 4 remotely operated vehicle (ROV), which is controlled from the surface. It is used for video and photo collection and carries a manipulator to grab waste. This micro-ROV is able to operate 300 m below surface and has no temperature restrictions.

TT: drone, RP: 306 [t/year], cost: 99000 [USD/year]

The Ocean Cleanup System 001 (Wilson)

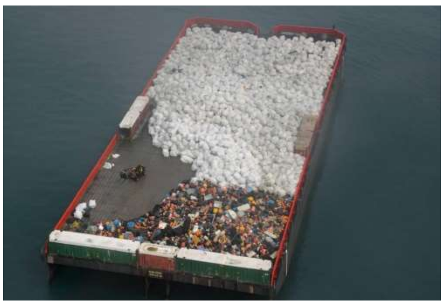
The Ocean Cleanup has just launched its first system, which is inspired by conventional oil recovery measures. It is a 600 meter floater that floats at the water surface and has a tapered 3 meter deep skirt attached below. The wind and waves propel the system, as the floater sits just above the water surface, while the plastic is primarily beneath it. The system moves faster than the plastic, allowing plastic to be captured.

TT: boom, RP: 214 [t/year], cost: 600000 [USD/year]

Algalita

Algalita is founded by Charles Moore (discoverer of the 'plastic soup'). The foundation does many explorations for water sampling, manta-trawling and ghost net collection. Furthermore they have developed 'debris science investigation kits' containing basic water sampling equipment and protocols for young scientists.

TT: expedition, RP: 98 [t/year], cost: 400000 [USD/year]



Gulf of Alaska Keeper

Gulf of Alaska Keeper is a local initiative by Alaskan volunteers that use a network of small, privately owned vessels (fishing, tugs etc.) and collection barges. They manually collect marine litter from near-shore and beaches and bring it to a mothership. They do not use any specialized technologies and rely on basic and accessible tools.

TT: manual labour, RP: 1.7 [t/year], cost: 90000 [USD/year]

Local initiatives in East-Asia

This example is a collection of local initiatives from East-Asia. In countries as Indonesia many people depend on 'fishing' for plastics. If they have any tools (but it mostly bare hands) they use simple rowing boats, sticks and nets to collect the most valuable types of plastics. The working conditions are hazardous and the income is low.

TT: manual labour, RP: 0.2 [t/year], cost: 3300 [USD/y]

Nordic Ocean Watch – #Tavaha

An environmental collective dedicated to taking care of the ocean. They rely on locals that manually collect plastic waste in Nordic areas by using their own tools (simple boats, nets, buckets etc.). The Nordic Ocean Watch has multiple recycling stations along the coast of Norway to store and research ocean plastics. They also use smart technologies as the Blueye ROV and Trashtag technology, that enables them to map areas and scan for ocean plastic.

TT: manual labour, RP: 8 [t/year], cost: 66000 [USD/year]

Race for Water - Odyssey

Odyssey is a high-tech integrated mixed solar-hydrogen-kite powered ocean-going catamaran that promotes innovative solutions for transforming plastic waste into energy resources. The on-board technologies vary over time (depending on the involved research programs), but usually include trawling technologies, water sampling and smart imaging technologies.

TT: expedition, RP: 98 [t/year], cost: 400000 [USD/year]

Waste Shark

The Waste Shark is a Dutch invention that recovers plastic from rivers and waterways. The autonomous vessel scans and maps the environment, and localizes the plastic waste. It can store up to 500 kg of plastic. Besides that, the waste shark is equipped with multiple sensors so it can measure the local water depth, temperature and oxygen levels.

TT: drone, RP: 0.3 [t/year], cost: 3300 [USD/year]

Upgyres & Watreco

Upgyres is a global venture that works jointly with industry programs to design and build biologically intelligent plastic recovery robots and zero emissions, zero fuel, zero ballast water, plastic processing and transport vessels. The bio-robots bring the recovered plastic to a floating, eco-extraction, upcycling offloading vessel.

TT: drone, RP: 0.3 [t/year], cost: 3300 [USD/year]

Blue Whale Boat

This is a local initiative in the city of Amsterdam where tourism and plastic recovery is combined. With simple fishing nets and hooks plastic is recovered during a city-tours. The collected plastic is recycled into whale boats – the same kind of boats that are used for the recovery job itself.

TT: expedition, RP: 1.1 [t/year], cost: 33000 [USD/year]

4.2 ANALYSE: OPERATIONAL EXPENSE AND RECOVERY POTENTIAL

The first assessment of data is a coarse filter based on an indication of costs and recovery potential. This paragraph describes the application of this first assessment and what kind of assumptions were necessary to prepare for the first selection. The two most important criteria for now, are a first estimation of cost and recovery potential.

4.2.1 The first two technical parameters: Costs and Recovery Potential

During the search (divergence) for technologies, many concepts were collected. Some of the concepts apply similar technologies, such as PGS and the Great Bubble Barrier, or Algalita and Trawlshare. However, the way the technology is integrated in the overall concept, has a large influence on performance. This means that similar technologies can still have a very different recovery rate, depending on the way it is utilized. For this reason, all the obtained concepts are analysed, instead of just the used technology. When we have found the best combination of technology and overall concept, we can easily select the most favourable combinations for further assessment. For now, the two most important parameters are:

- Cost as combination of operational and voyage expenses in USD per year. This is a basic cost estimation for one operational day using this technology on board of a particular concept. The feasibility of the technology heavily depends on the cost of investment and cost during operation. The emphasis is on the operational part during this first assessment, because the investment costs were found to be less reliable to predict since the varying stages of concept development. The cost-function is still a rough estimation and takes into account manning cost M, maintenance cost MN and fuel cost FC.

$$C = M + MN + FC \quad \text{Eq. 4.1}$$

- Recovery Potential: in tonnes per year. The effectiveness of the technology heavily depends on the area that the technology will explore during its search for plastics. The potential depends on the concentration of plastic in a certain area. As the literature study showed, the vertical distribution of plastics is not necessarily homogeneous, so a certain depth function is recommended to include. For now, the recovery potential is based on an area A, depth T and average concentration ρ.

$$RP = A \cdot T \cdot \rho \quad \text{Eq. 4.2}$$

Both parameters are a first estimation. In the third step of the methodology (the case studies) these two parameters will be revisited with a higher level of detail. For this first screening, a higher level of detail would be cumbersome and quite irrelevant. To make a fair comparison, the ratio between the cost and the recovery potential will be calculated as well. This will give us insight into the cost of recovering one tonnes for a specific application of a technology. Table 4.1 shows the build-up of cost and recovery potential for all the obtained concepts.

4.2.2 Necessary assumptions

Most technologies did not publish their operational costs, but did report the fuel tank capacity, type of fuel and time it could operate using the full capacity of the fuel tanks. From there on, calculation of the fuel consumption was straight-forward. Human involvement was mentioned for every technology that is included in this analysis. Although some technologies did not use any fuel, all technologies included human involvement to a certain extent. Even the autonomous technologies currently need human assistance when transferring plastics from vessel to another type of carrier or shore.

For the calculation of plastic, the density of plastic was assumed to be $\rho = 69 \text{ tonnes/km}^3$, which is based on the concentration of ocean plastic in the top layer (0 – 5 meter from water surface) of the water column (Lebreton *et al.*, 2018).

4.2.3 Results

The results of the first assessment are given in Table 4.1 and Figure 4.1.

			RECOVERY POTENTIAL			COST				COST/TONNES
name	passive / dynamic	technology type	recovery area [m2/hour]	recovery depth [m]	recovery potential [t/year]	manning [$/year]	maintenance [$/year]	fuel [$/day]	total cost [USD/year]	[$/t]
Floating horizon	dynamic	boom	18520	3	18.4	3000.0	310	0	3310	180
Rozalia & Parley	passive	drone	4630	200	306.7	90000.0	9310	0	99310	324
Protei & Scoutbots	dynamic	boom	9260	0.5	1.5	3000.0	310	0	3310	2159
Trawlshare	dynamic	trawling	22224	4	29.4	60000.0	6207	60	66267	2251
The great bubble barrier	dynamic	bubble curtain	9000	4	11.9	30000.0	3103	0	33103	2776
The Ocean Cleanup 001	passive	boom	216000	3	214.6	120000.0	12414	2500	134914	629
4Ocean	dynamic	trawling	22224	4	29.4	90000.0	9310	60	99370	3375
Algalita	dynamic	expedition	74080	4	98.1	360000.0	37241	0	397241	4048
Race for water - Odyssey	dynamic	expedition	74080	4	98.1	360000.0	37241	0	397241	4048
Sea Cleaning Drones	dynamic	drone	4630	0.5	0.8	3000.0	310	0	3310	4317
Spindrift	dynamic	expedition	74080	4	98.1	360000.0	37241	1800	399041	4066
PGS	dynamic	bubble curtain	1481600	2	981.4	750000.0	77586	34200	861786	878
Nordic Ocean Watch	dynamic	manual labour	25000	1	8.3	60000.0	6207	0	66207	7996
REV Ocean	dynamic	expedition	74080	4	98.1	360000.0	37241	2200	399441	4070
Seabin	dynamic	pump + filter	1800	0.5	0.3	3000.0	310	0	3310	11106
The inner harbour wheel	dynamic	pump + filter	9000	0.5	1.5	15000.0	1552	0	16552	11106
Waste Shark	dynamic	drone	1800	0.5	0.3	3000.0	310	0	3310	11106
Upgyres & Watreco	dynamic	drone	1800	0.5	0.3	3000.0	310	0	3310	11106
Blue Whale boat	dynamic	expedition	32000	0.1	1.1	30000.0	3103	0	33103	31234
Gulf of Alaska Keeper	passive	manual labour	5000	1	1.7	60000.0	6207	120	66327	40052
Local initiatives Asia	passive	manual labour	5000	0.1	0.2	3000.0	3103	0	6103	36857
Recycled Park	passive	filter	180	0.5	0.0	3000.0	3103	0	6103	204759

Table 4.1 First estimations of recovery potential and costs

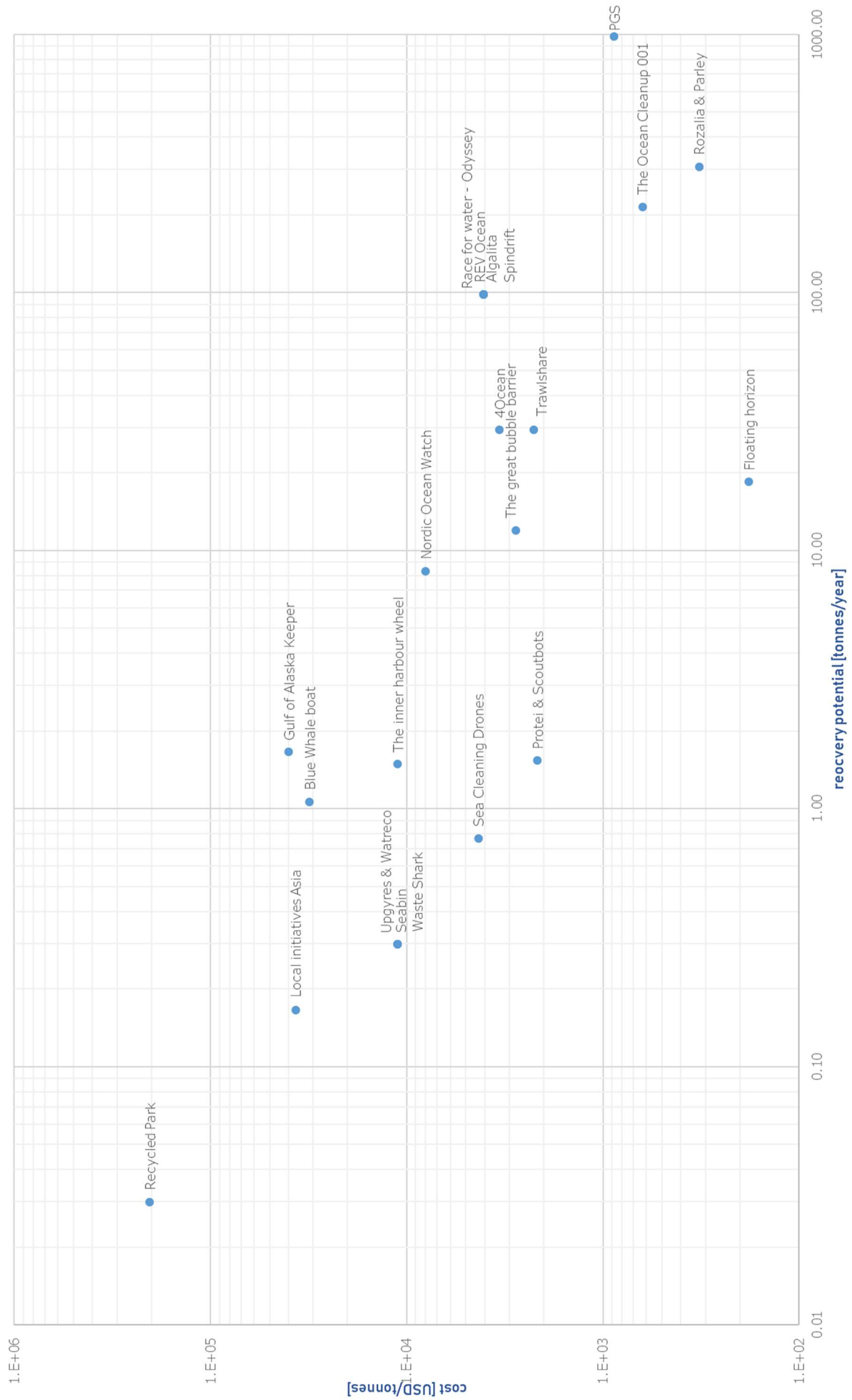


Figure 4.1 Cost per recovered ton on the y-axis and recovery potential on the x-axis.

4.3 CONVERGE: SELECT MOST FAVOURABLE CONCEPTS

The different technology types that were found during the collection of concepts:

- Trawling technologies: vessels that use a trawling system to collect waste.
- Autonomous drones: unmanned vessels, mostly equipped with a robot arm to grab plastic waste, which was optically detected.
- Air bubble curtains: air bubble barriers that are towed or locked at one location. Plastics stick to the air bubbles and move to the surface.
- Manual labour: the most inefficient, but affordable way of waste collection.
- Pumps and filters: collection of water by a pump and filtering. Mostly applied in shielded areas.
- Booms: closing in of floating plastics, can be applied on different scales (width varying between 6 and 600 meter).
- Expedition: this is not a technology on itself, but usually has a combination of the mentioned technologies onboard.

The way the technologies were integrated in the overall concept had a very large influence on the estimation of the recovery potential. For example, the concepts of PGS and The Great Bubble Barrier both rely on air bubble curtain technologies, but the estimation of the recovery potential (980 versus 12 tonnes per year) and cost per tonnes of recovered plastic (878 versus 2778 USD) differ tremendously. For the converging of most favourable concepts, we have looked into the best application of technologies, based on the ratio between recovery potential and estimated cost per tonnes. This means that the best application of technologies can be found in the lower right corner of the diagram (far right on the x-axis equals a high recovery potential, far down on the y-axis means low cost). The most promising application of technologies are found to be:

- Rozalia & Parley (best autonomous drone technology)
- The Ocean Cleanup 001 (best boom technology)
- Floating Horizon (second best boom technology)
- Trawlshare (best trawling technology)
- PGS (the best air bubble curtain technology)
- REV/Spindrift/Odyssey/Algalita (best expedition technology)

The concepts that relied on manual labour or simple filters did not result in any realistic solutions. For both technology types the recovery potential is extremely low, which caused a significant increase of cost per tonnes. All the applications of technologies that are not listed above will be excluded from further analysis.

The selected applications of technologies will be used for future analysis. Some of these applications will be changed slightly to increase its effectiveness. For example, many similar expedition concepts were obtained during the analysis. For further analysis, similar applications of technologies are combined into the following concepts (see Figure 4.2):

- Autonomous drone technology: unmanned underwater drone that has the ability to locate and capture ocean plastics and return them to a mothership. This concept can be applied in both protected areas and deep sea areas.
- Boom technology: a 600 meter wide passive barrier that is moved by ocean currents, wind and waves. The plastic will be closed in by the structure and can be picked up by an external vessel. This is an ocean-based concept.
- Trawl technology: 10 meter wide trawl structure that can be towed behind or next to an existing vessel, and can be used on rivers or near-shore waters.
- Air bubble technology: 200 meter wide air bubble curtain 5 meters below water surface.
- Expedition technology: a combination of trawling, boom technology and use of autonomous drones applied to research and expedition vessels.

4.4 INTERMEDIATE CONCLUSION & RECOMMENDATIONS

In this first step of the assessment, a high-level screening has been developed to identify the most promising technologies and concepts. When assessing different types of technologies, it is only useful to use parameters that actually allow a fair comparison. For that reason, the cost per tonnes ratio is the most important parameter. However, the recovery potential does not provide any ratio, but gives insight into the overall impact of the concept. It might have an efficient cost per tonnes ratio, but it will hardly have any positive impact if the recovery potential itself is low. It should be mentioned that those two parameters are not sufficient when deciding which concept is the most favourable; many more aspects contribute to the performance and effectiveness (see qualitative judgment, Chapter 5).

When applying this 1st step of the methodology, it is recommended to:

- Update the database on a regular basis. Many interesting projects were found, but were not yet ready to be included into a database due to a lack of accessible data.
- Look for concepts for both this specific purpose as for solutions from other sectors, in order to collect a diverse selection of technologies.
- Select a diverse group of concepts for further assessment to increase the quality of the overall assessment. The 3rd and final step will offer the opportunity to look into more details of specific concepts.
- Furthermore, it is recommended to develop a water depth-dependent function for the density of plastics. For now, one density has been used for the calculation of recovery potential, which was a big assumption. For future use, it would be preferable to link the density of plastics to the global maps as discussed in paragraph 2.3.3. Unfortunately, these models are currently not verified, so it would not result in any improved reliability of the recovery potential estimation.

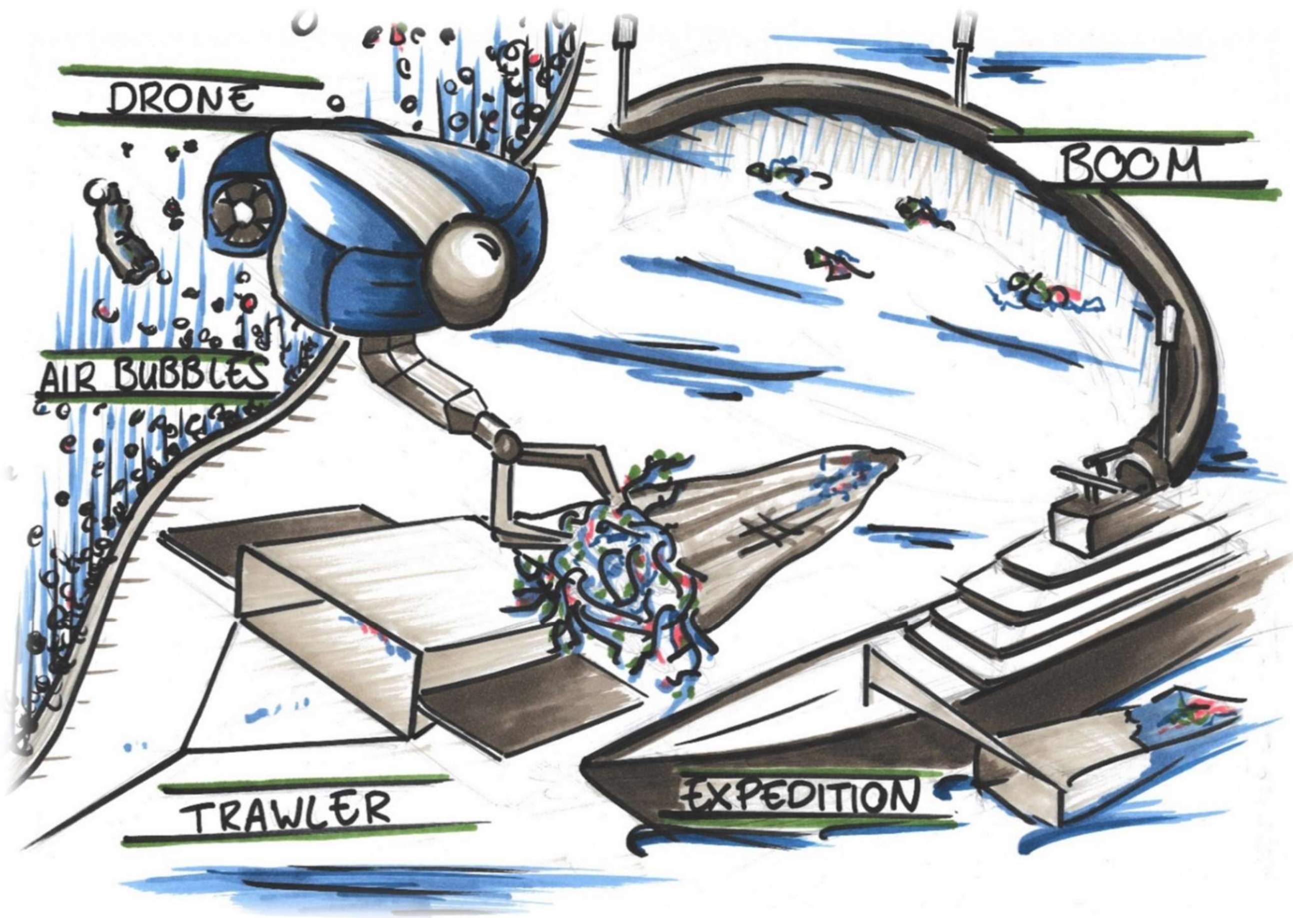
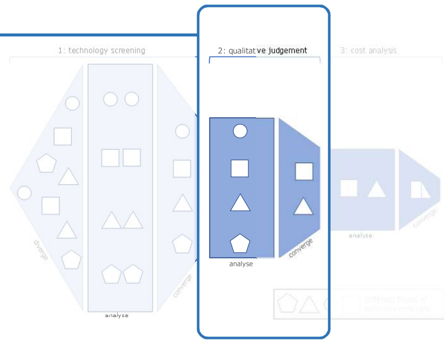


Figure 4.2 Overview of the five favourable concepts: the drone, boom, air bubbles, trawler and expedition.© Vera Terlouw

5 QUALITATIVE JUDGEMENT



This part of the methodology focusses on the qualitative factors and compares concepts in a pairwise manner. As the Strategic Solution Space for ocean plastic recovery (Figure 2.14) proved, it is of great importance that the concept is well-connected to society, environment and technology in order to create sufficient incentives to act. Therefore, this part of the analysis focusses on a qualitative assessment of the selected concepts.

ADDED VALUE: This model balances qualitative and ethical aspects with technological performance. The benefit of plastic recovery is not necessarily based on cost only, but can be maximized using a qualitative assessment considering its societal, environmental and technological benefits. After this step, one can focus on the concepts aimed for the maximum benefit, and investigate further on a cost-level during the case studies (Chapter 6). On a higher level, such an approach can be used when looking into assessment of solutions for anthropogenic problems.

5.1 ANALYSE: MODEL CRITERIA

The criteria are based on the qualitative findings form the literature study and technology assessment. The literature findings are used as main input for the identification of qualitative criteria for to assess the strategies of each of the concepts.

5.1.1 Identification of criteria

The criteria are based on the parameters of the Strategic Solution Space (Figure 2.14). Each field of the solution space (technology, society and environment) is subdivided into smaller parts which address particular strategic aspects or design requirements. The related sustainable development goals helped to articulate the qualitative criteria (Figure 2.15).

For the technology assessment, the criteria are:

- Scalability, subdivided into *simplicity* and *cost/recovery ratio*:
  The technology should be easily scalable to optimize the cost per tonnes of recovered plastic. The scalability will be judged based on its simplicity (minimal complexity induces easy scaling), and the cost/recovery ratio should have a high recovery potential for a low cost (both operational and investment) to be seen as a main incentive to scale up.
- Safe Operations, subdivided into *human involvement* and *human risk*:
  The well-being of the involved people should be safeguarded at all times during the operation. The operation should not increase or evoke human risks (for human risks see the bow tie model and also paragraph 7.2.1). The safe operations will be judged based on the extent of human involvement and human risk.
- Durable and resilient design, subdivided into the *technology readiness level*, *weather window* and *redundancy*:
  Durability and resilience of design is of great importance, since many technologies will be facing extreme conditions. The level of development of the design itself is assessed by the Technology Readiness Level. The weather window is judged by the estimated operability for the environment the technology will be deployed in, and the long-term durability is judged on the redundancy of its most essential parts (what needs to be in place in order to function, and can it be easily replaced when broken).

For the environmental assessment, the criteria are:

- Ocean restoration: subdivided into the *recovery potential* and *minimal emissions*:
  As previously found in the trajectory study (paragraph 3.1.2) the best solutions help to reduce the total accumulated amount of plastics in the ocean, and by doing so restore the oceans. The ability to contribute to ocean restoration is judged on the recovery potential, and on estimation of emissions that were caused by the operation itself. Obviously, no harmful emissions will be the best option for proper ocean restoration.
- Securing biodiversity will be judged based on the *bio-friendly design*:
  The recovery operation should not cause any harm to sea life. The securing of biodiversity will be judged on its bio-friendly design. For example, if there is any chance of bycatching animals.
- Reducing harmful human impact will be judged on the *preventive and / or reactive actions* related to the concept that reduce harm to and from humans.

For the societal assessment, the criteria are:

- Promoting employment and new businesses will be judged on its *economic sustainability*:
  The economic sustainability of businesses is an important incentive to start acting. A healthy and inviting business must support a local community and offer paid employment.
- (Cross-border) cooperation is judged on the *involvement from different sectors*:
  The problem of ocean plastic pollution involves many sectors (manufacturers, collectors, consumers etc.) that are connected by a circular economy. These sectors must cooperate and share responsibility. This cooperation is judged on its involvement and connection to these third parties.
- The transparency of the value chain is judged on the *clarity of the post-collection treatment*:
  This factor puts emphasis on the subsequent step right after plastic recovery. The operation must have a clear plan about the post-collection treatment including where it is going, and what it will be used for (closed loop recycling, incineration, etc.).

On June 20, 2018 a creative session[13] was held with the Maritime Advisory Department of DNV GL. These findings were used as input for the formulation of the criteria above. The weights of the criteria were also influenced by these findings.

5.1.2 Weight of each criterion

Each criterion has its own weight to allow prioritizing of criteria. The weight factors are a result of multiple discussions with experts[13,14]. As found earlier, there are many cultural and societal differences that will have an influence on what is considered as important in such an analysis. When applying this methodology, it is recommended to discuss the weights of the criteria with an expert panel that can represent all stakeholders to avoid any personal bias. The cultural and societal differences should be very well-considered when deciding on the weight factors of the criteria. Eventually, these weights will decide what kind of aspects are seen as the most important and therefore the most influential in the design process. For example, countries or communities in Indonesia might prioritize economic

[13] Creative session was the 'Lunch & Learn event' that was held on June 20, 2018 at DNV GL HQ in Høvik, Norway and was attended by 25 specialists and consultants from the Maritime Advisory Department. It was a 45 minute meeting aimed to evoke creative thinking and collect as much input as possible. The meeting had the following parts: brief overview of plastic pollution problem definition, including an explanation of the Strategic Solution Space and existing concepts. Then, the specialists were asked to work in groups and look into a design challenge: With a time-restriction, come up with your most effective plan to recover plastics if you could spend 10 million NOK (roughly 1.3 million USD). During the debrief the proposals were discussed and the specialists defended their personal solutions, and explained what made them so good. The last challenge was to share any advice that could benefit the development of the methodology and the rest of the project. My role was to present and mediate the session. After the meeting the results were investigated, and used a source for the formulation and prioritization of criteria. The main findings were that the technical concept should be as simple as possible (including a proof of concept) so it can be produced locally and easily scaled. Also, the recovery operations should not rely on fossil fuels, but should use green energy sources. Furthermore, recovery operations should take place in areas with a high concentration of plastic pollution and the recovery operation should be well-monitored, so the long-term improvements can be identified. Ultimately, the recovery operations should not create any new problems to the world: no added risks for humans, sea life or nature.

sustainable business models whereas countries like Norway might have better access to funds so businesses do not necessarily need to be economically sustainable. On the other hand, Norway and Indonesia might have a different view on risk acceptance; Norway could possibly prioritize its safe operations whereas Indonesia might be less risk-averse. Because of these cultural and societal differences, it is of great importance to use an expert panel that represents the actual stakeholders.

For this particular run-through of the methodology, the weights of the criteria are:

	CRITERIA AND ITS WEIGHTS			COMMENTS
TECHNOLOGY	scalability	simplicity	1	The cost/recovery and the simplicity are both important criteria, but in this case not heavily judged since they are both thoroughly investigated in the technology assessment (step 1) and cost-analysis (step 3).
		cost/recovery ratio	1	
	safe operations	human involvement	1	
		human risk	1	
	durable and resilient design	technology readiness level	3	Technology readiness level is a prioritized technological criterium, since the proof of a working concept is an important prerequisite for production, deployment and scaling.
		weather window	1	
		redundancy	1	
		total weight technology	9	
ENVIRONMENT	ocean restoration	recovery potential	1	The impact on the biodiversity and harmful impact are prioritized, since one of the most important factors was that the operation should not add any harm or risk to life.
		minimal emissions	3	
	securing biodiversity	bio-friendly design	3	
	reducing harmful impact	preventive & reactive risk management	2	
		total weight environment	9	
SOCIETY	promoting employment & businesses	economically sustainable	3	All factors of the societal criteria are equally valued, since no local prioritization has been found during the conversations with the expert panels.
	cross-border cooperation	stakeholder involvement	3	
	transparency	clarity of post-collection treatment	3	
		total weight society	9	

Table 5.1 Criteria breakdown and individual and total weights

Of course, the values of the weights are up for a lot of discussion; which is the point exactly. The reader might find him/herself disagreeing with the values, but it is important to mention that the values represent a collaborative judgement by stakeholders and together avoid personal bias. Furthermore, the values used in this step are well-considered but are mainly used to demonstrate the application and purpose of this design tool.

5.1.3 Recovery Concepts

A brief repetition of the chosen concepts by the technology assessment (Figure 4.2 and paragraph 4.3):

- Autonomous drone technology: unmanned underwater drone that has the ability to locate and capture ocean plastics and return them to a mothership.
- Boom technology: a 600 meter wide passive barrier that is moved by ocean currents, wind and waves. The plastic will be closed in by the structure and can be picked up by an external vessel. This is an ocean-based concept.
- Trawl technology: a 10 meter wide trawl structure that can be towed behind or next to an existing vessel, and can be used on rivers or near-shore waters.
- Air bubble technology: 200 meter wide air bubble curtain 5 meters below water surface (ocean-based concept).
- Expedition technology: a combination of trawling, boom technology and use of autonomous drones applied to research and expedition vessels.

5.1.4 Comparative judgement

The concepts are compared using a rating system, where the concepts are judged based on each criterion, based on the following system:

1:	3:	5:	7:	9:
Very poor: the concept does not consider the criteria at all	Poor: concept shows consideration of criteria, but does not fulfil needs and /or affects negatively	Sufficient: it does meet the requirement, but does not fully fulfil needs either	Good: meets the requirement very well and fulfils needs	Excellent: (nearly) perfect performance and serves as a great example as best practice

Table 5.2 Rating system for comparative judgement

The reason for using this type of rating, is that the numbers are based on a qualitative spectrum. The numbers are not sequential to create a larger deviation in outcomes, with the advantage that it will be easier to differentiate the best concepts.

It is of great importance that all concepts are judged simultaneously to facilitate an equal comparison of concepts. It is recommended to start with one specific criterion, and discuss the individual rating of each of the concepts among a group of experts. The advice from the discussion groups[13,14] was used to formulate the comparative judgement.

[14] The results and next step were discussed during a conversation with experts was held on June 21, 2018 at DNV GL in Høvik, Norway and was attended by Per Marius Berrefjord (Senior Vice President and Business Development Leader), Jens Laugesen (Chief Specialist), Atle Ellefsen (Chief Naval Architect) and Arnstein Eknes (Business/Segment Director Special Ships). During this conversation the following challenges were discussed: criteria: what kind of criteria need to be in place for recovery assessment? And how do these criteria apply to local solutions (from the most simple trawlers to drones) and ocean-based solutions? The results of this meeting were used as main input for the qualitative judgement of the chosen concepts.

5.1.5 Results

The table below shows the comparative judgement of the five concepts. The overall result is given on the next page.

	CRITERIA AND ITS WEIGHTS			DRONE 1.	BOOM 2.	TRAWL 3.	AIR BUBBLE 4.	EXPEDITION 5.
TECHNOLOGY	scalability	simplicity	1	3	9	9	1	3
		cost/recovery ratio	1	7	5	5	5	3
	safe operations	human involvement	1	5	7	3	5	3
		human risk	1	3	5	7	3	3
	durable and resilient design	technology readiness level	3	7	9	9	3	5
		weather window	1	3	3	5	3	5
		redundancy	1	3	7	7	3	3
		total weight technology	9					
ENVIRONMENT	ocean restoration	recovery potential	1	7	7	3	9	1
		minimal emissions	3	7	9	5	1	3
	securing biodiversity	bio-friendly design	3	5	7	5	3	3
	reducing harmful impact	preventive & reactive risk management	2	5	7	7	5	5
		total weight environment	9					
SOCIETY	promoting employment & businesses	economically sustainable	3	5	3	9	1	9
	cross-border cooperation	stakeholder involvement	3	5	5	9	3	7
	transparency	clarity of post-collection treatment	3	7	5	9	5	5
		total weight society	9					

Table 5.3 Criteria breakdown including comparative judgement

The final result of the qualitative judgement can be found in Figure 5.1.

Figure 5.1 Results of qualitative judgement. The spider plots show the compatibility of the concepts with the criteria for technology, environment and society

5.2 CONVERGE: SELECT MOST FAVOURABLE CONCEPTS

After the comparative judgement of the concepts (Table 5.3), the results were gathered and plotted (Figure 5.1). The spider plots show the compatibility of the concepts with the criteria for technology, environment and society. The best concepts can be selected based on the largest coverage, meaning that the area covered by the plot shows the extent that the concept meets the criteria. After a visual investigation, it is quite clear that the 'boom' and 'trawl' have the largest coverage of the spider plot, and therefore are the most favourable. The decision can be supported by determining the significant variation in results. The 'boom' concept scores at least 8% better than the three least favourable concepts, and the 'trawl' concept scores at least 18% better. Assuming that a variation of 5% is an acceptable significant variation, the two concepts can be seen as favourable over the rest of the alternative concepts.

5.3 INTERMEDIATE CONCLUSION & RECOMMENDATIONS

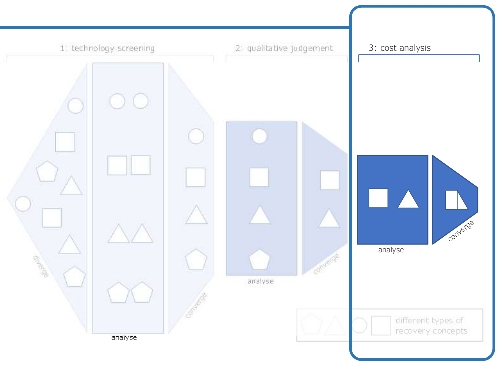
The purpose of this decision-model is to offer a quality-based balance between ethical aspects and technological performance. The benefit of recovery operations must be considered on not just a financial level, but must assess the impact on society and environment. During this step, the most promising technological concepts turned out to not necessarily be the best ones, mostly due to a lack of societal or environmental impact. Now that the most beneficial concepts are obtained, only these ones have to be further investigated by a cost estimation to look into the financial feasibility. It is advantageous to have ruled out some of the concepts before further investigation, since the cost estimations can be quite tedious. By doing so, we can spend time on concepts that have a high likelihood of actually turning the problem into value.

Another advantage of this qualitative approach was that many criteria were considered that would have been hard to assess when only a quantitative approach had been used. Now, a quite natural parting happened between (in-)direct benefits and cost (next Chapter).

When applying this step of the methodology it is recommended to:

- Have a diverse selection of concepts to assess.
- Ask for expert advice for determining the criteria weights and judgement of concepts.
- The group of experts should be diverse as well to avoid any local bias.
- Be aware of the fact that this step can be quite cumbersome: especially when the expert panel represents a diverse group of stakeholders, a passionate discussion is lurking. Proper time-management and mediation are both essential parts of such sessions.
- The discussions with experts usually produce a lot of input and new insights. It is recommended to take minutes, since many of those insights are valuable for future design recommendations.
- When visual inspection of the spider charts does not give any decisive answer, it is recommended to strengthen the spider charts with calculations. A simple summation of ratings for each concept, and taking into account the weights of the criteria, will probably help when selecting concepts for further analysis. If there are multiple concepts with a similar score, it would be recommended to select all these concepts for the next step. Overall, it is important to consider the significant variation of the outcome.
- Select more than one concept for the next, quantifying step to increase reliability of final outcome.

6 COST-ANALYSIS: CASE STUDIES



The two favourable concepts are used as the starting point for two business cases. These business cases will zoom in on the direct cost and the recovery potential related to the plastic recovery operations, and will allow us to compare outcomes.

ADDED VALUE: Looking into two potential cases, allows us to compare and look for relations. The process of estimating cost and recovery potential will gradually identify the biggest contributors and development of estimation equations. These relations and contributors will be a great source of information for design improvement and future recommendations.

6.1 ANALYSE: TWO CASE STUDIES

Resulting from second step of the methodology, there are two interesting concepts to look further into from a business case perspective. Both concepts score relatively well on the qualitative assessment, and are therefore chosen for further investigation of its cost and recovery potential. The two cases describe one ocean-based concept and one river-based concept. The total estimated cost will be compared to their abilities to recover plastics. First, it will be explained what is considered and what is neglected in the case studies. Then, the method will be explained and eventually be applied.

6.1.1 Case Study A: Ocean Solution

This case is based on what was found to be the best ocean-based concept from the database and the qualitative assessment and is inspired by the latest concept of The Ocean Cleanup. The design describes an oil recovery inspired approach using a wide floating boom structure with a skirt attached to it. The boom structure is towed to the required location by two vessels: one larger offshore support vessel, and one smaller tug. See Figure 6.1 for a schematic overview.

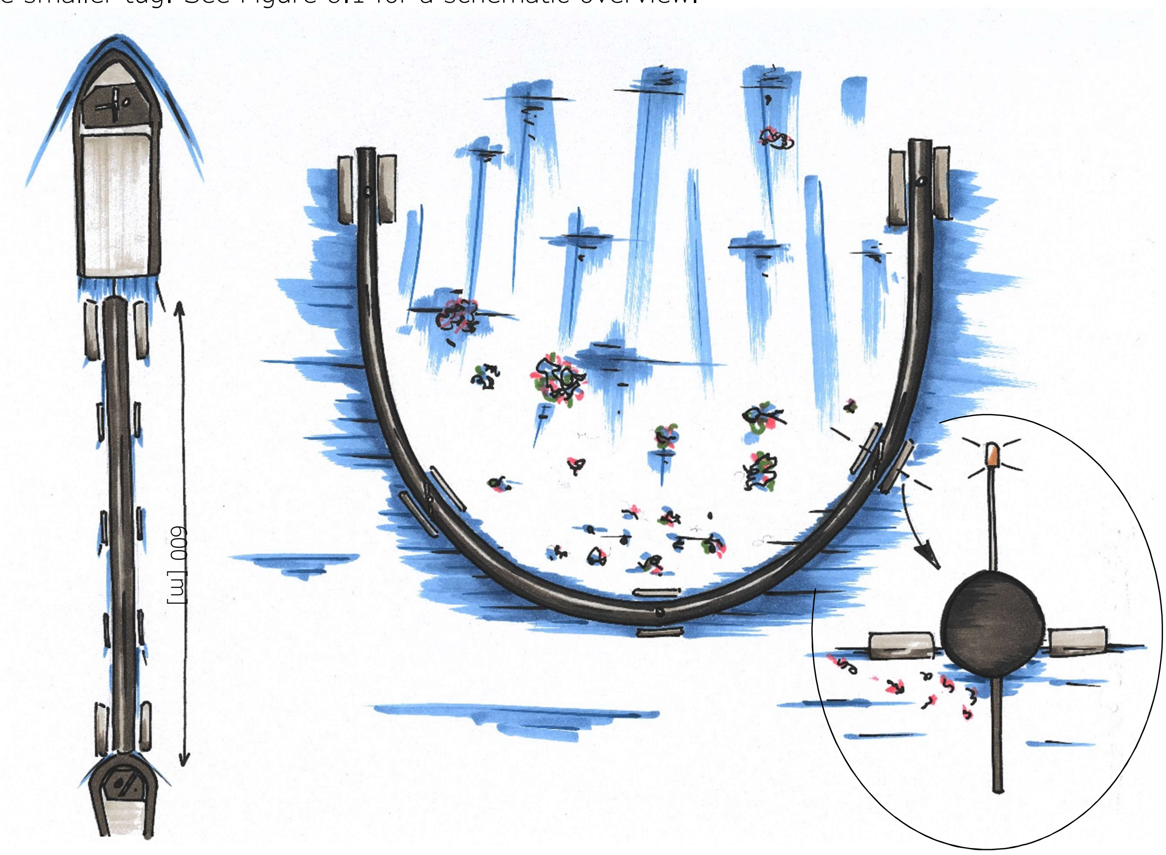


Figure 6.1 Schematic overview of case study 'Ocean'

During this case, several assumptions were made:

- The boom itself is the only part with an investment cost. For now, the structure is a one-of-a-kind, but has the possibilities for scaling up. The investment cost of the structure itself is estimated to be 8 million USD. The vessels will cover the operational costs and voyage, since they will tow the structure out to sea.
- The structure and vessel will leave from San Francisco and sail towards the North Pacific Gyre, a distance of 1100 nautical miles. Their average towing speed is estimated to be 4 knots. Once the structure has reached its destination, the offshore support vessel can be utilized to pick up the collected litter and sail back to port.
- The floating boom structure must remain out at sea for 2 years continuous (design is extensively tested on model scale and by numerical testing and should be able to survive at sea for this duration of time (The Ocean Cleanup, 2015)). The offshore support vessel will collect the litter once every two months, and take care of any maintenance. The tug is only needed for the towing process. The calculations of the offshore support vessel are based on the specifics of (Damen Shipyards Gorichem, 2018), (Stopford, 2009) and (Drewry, 2009), which will be elaborated on in both the method and results sections.
- A fully equipped crew is needed during the towing operation. During the litter pickup, it is assumed that a smaller crew is necessary. A full crew includes a master, 4 officers, 3 engineers, 1 bosun, 8 seamen and 1 catering (total of 18 crew). Their main responsibilities will be to navigate to the final location and to monitor the structure in waves during the tow-out. In case of any minor damage, the crew must be able to apply corrective maintenance actions. The litter pick up will be an easier operation and requires a master, 2 officers, 1 engineer, 1 bosun, 6 seamen and 1 catering (total of 12 crew). Then, the main responsibilities are to navigate the support vessel during the plastic recovery (maintaining a safe distance from the boom structure) and the plastic recovery itself. It is assumed that the crew and ship has 10 years of experience.
- The local concentration in the North Pacific Gyre has been used for the calculation of recovery potential. This concentration of floating plastics is estimated to be 0,0463 t/km^2 (Lebreton *et al.*, 2018). This is the most reliable data source nowadays, but it should be mentioned that even this source has its disadvantages. This is further described in the research recommendations.
- The total Recovery Rate η_r will be based on a reasonably good pick up rate (η_{pickup} =0,9), a loss factor of (η_{loss} =0,50), a weather envelope ($\eta_{weather}$ =0,9) and the collection of waste as ($\eta_{collection}$ =0,50). The pick-up rate has this value, mainly due to the width of the structure. If the floating boom structure works the way it is intended to work, it should be able to close in the majority of floating plastics within its radius. The weather envelop is estimated to be 0.9, since the model and numerical tests proved that the structure should be able to withstand quite some external forces. Even though the structure itself is expected to remain intact, it is expected that overflow and underfill of plastics will be a big disadvantage of this system, which is taken into account by the loss factor. Another disadvantage is the unstructured pick up of the plastics by an external vessel, which is the reason for the low collection factor. The calculation of the total Recovery Rate will be further described in the results section.

6.1.2 Case Study B: River Solution

The second business case focusses on a near-shore or river location where local fishing vessels can be used to collect plastics, see Figure 6.2. This concept relies on a standard trawling system that can be installed on existing vessels. The design of the trawler is simple, low-cost and can be installed and maintained by local communities. The parts of the trawler are modular, which allows easy repair and replacement of broken parts. The following assumptions were made:

- The local fishing vessel can be used during off-season and will be equipped with a custom plastic recovery trawl (width = 10 m) and crane, see Figure 6.2.
- The Damen Sea Fisher 2603 has been used as an example vessel (Damen Shipyards Gorichem, 2016).
- The vessel is operational for this purpose for 130 days a year, 12 hours a day and equipped with 3 crew members (1 master and 2 seamen). The average trawling speed is 3 knots and will not enter international waters.
- As found in paragraph 2.2.2 the origin from many plastics comes from land, which results in a high concentration in rivers and coastal areas. In this case, the average lower-bound of the concentrations in the top 20 polluting rivers, which is 2,46 t/km^2, have been used for this calculation (Lebreton *et al.*, 2017). Again, this is the most reliable data source nowadays, but also has its disadvantages. This is further described in the research recommendations.
- It is assumed that the river velocity is 2 knots. This is an average over a year for the top 20 polluting rivers. It should be mentioned that the flow of the rivers is subjected to seasons (Hajbane and Pattiaratchi, 2017), which is currently not taken into account.
- The investment costs will be roughly 6.000 USD and the concept will be in use for two years (5Gyres, 2016), this includes investment cost of replacing parts.
- The ratios for the voyage costs are based on (Stopford, 2009) and (Drewry, 2009). The operational costs use the same percentages as case A to make sure both cases are comparable.
- The total Recovery Rate η_r will be based on a pick up rate of (η_{pickup} =0,75), losses of (η_{loss} =0,75), a weather envelope of ($\eta_{weather}$ =0,75) and considering the near-shore location of the vessel, and an efficient collection of waste from the structure to a mothership ($\eta_{collection}$ =1). The pick-up rate is relatively high because the vessel is equipped with two ways to recover plastics (crane and trawl), but there is still a chance that the river current pushes the plastics away from the trawl. This current can also cause some losses after pick-up. The weather envelope is reasonable, since the vessels will be likely to operate in a shielded area.

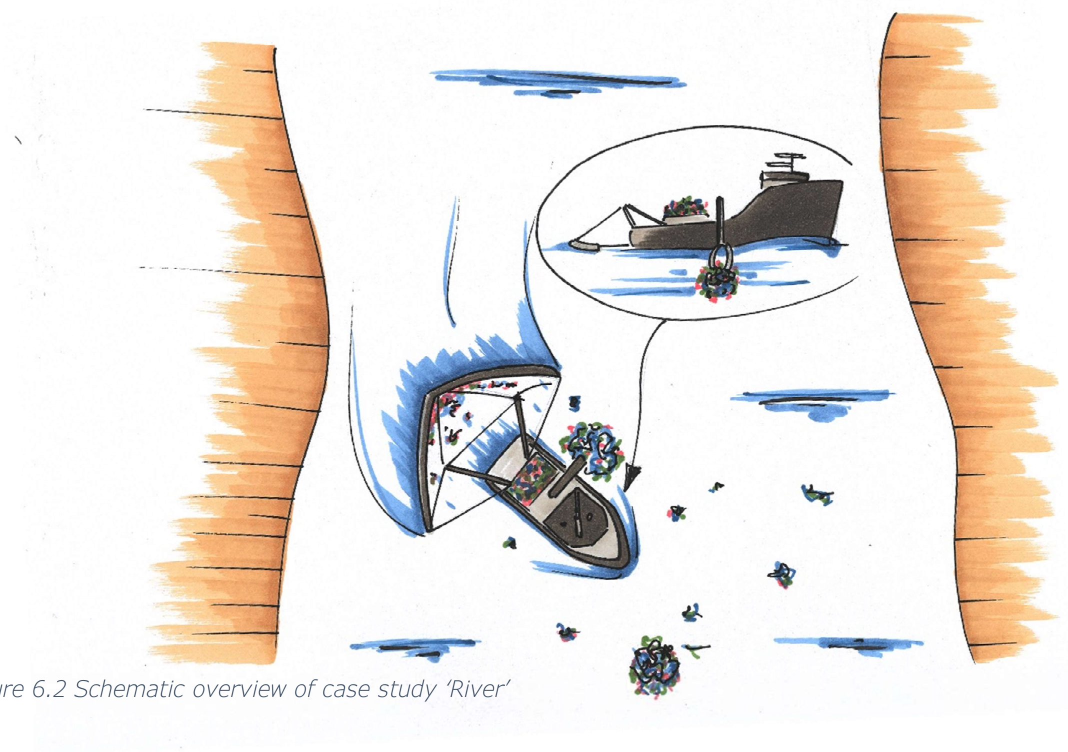


Figure 6.2 Schematic overview of case study 'River'

6.1.3 Method

Several equations were used to quantify the costs and benefits in a structured manner. The cost calculations mostly rely on Stopford's equations, the numbers and ratios between parameters are mostly based on data gathered by Drewry Shipping Consultants. Both Stopford and Drewry are widely used and globally accepted as reliable methods to approximate costs. Understandably, Stopford nor Drewry has published any standards or equations for plastic recovery. This resulted in several new equations, specifically developed to formalize plastic recovery cost calculations.

For the calculation of the operating cost, Stopford's equation has been used:

$$OC_{tm} = M_{tm} + ST_{tm} + MN_{tm} + I_{tm} + AD_{tm} \qquad \text{Eq. 6.1}$$

Where M is the manning cost, ST represents stores, MN is routine repair and maintenance, I is insurance and AD is administration, (see table 6.2 from (Stopford, 2009)). The percentages used are based on (Drewry, 2009), since this data source provided the most reliable data for those vessel types and operations.

Similar for the voyage cost:

$$VC_{tm} = FC_{tm} + PD_{tm} + TP_{tm} + CD_{tm} \qquad \text{Eq. 6.2}$$

Where VC represents voyage costs, FC is the fuel costs for main engines and auxiliaries, PD port and light dues, TP tugs and pilotage, and CD is canal dues, (based on table 6.3 (Stopford, 2009)).

When looking into potential income, the value of the material itself could be considered. Since there are many different types and quality differences, attaching a number to value density is not that straight-forward and can be seen as a relatively unexplored research field. Besides this, the value of the material itself is not the only parameter that could be considered here; according to Valuing Plastic the annual damage of plastics to marine ecosystems is at least $12 billion per year and Asia-Pacific Economic Cooperation (APEC) estimates that the cost of ocean plastics to the tourism, fishing and shipping industries was $1.3 billion in that region alone. In Europe, the potential costs for coastal and beach cleaning is estimated to be around $700 million per annum, (World Economic Forum, 2016). However, these numbers are too uncertain to be used for a calculation of the monetary value of recovered plastics. Since this value is so uncertain, the emphasis will be on the amount of plastic that can be recovered, and not on its monetary value, using:

$$RP = A \cdot C_p \cdot \eta_r \qquad \text{Eq. 6.3}$$

With RP as the Recovery Potential in tonnes, A as area in km^2, C_p as the local concentration of plastics in t/ km^2 and η_r for Recovery Rate which is a value between 0 and 1, and is defined by:

$$\eta_r = \eta_{pickup} \cdot \eta_{loss} \cdot \eta_{weather} \cdot \eta_{collection} \qquad \text{Eq. 6.4}$$

Where η_r is the total recovery rate, η_{pickup} is the efficiency of pick up by the system itself, η_{loss} are the losses caused by overflow and underfill, $\eta_{weather}$ is the effect of the weather envelope and $\eta_{collection}$ is the efficiency of collection of plastic when it is transferred from the system to the next step in the value chain. All variables are judged on a scale from 0 to 1.

$$A = W_{solution} \cdot \Delta v \qquad \text{Eq. 6.5}$$

The area A is calculated by W for the width of the technology, for example the width of a barrier, and delta v as the total Recovery Velocity. The total Recovery Velocity is a summation of the velocity of the technology itself and the velocity, flow or current of the water. The direction of both velocities should be taken into account when calculating the total Recovery Velocity.

Both business cases report a cost of the operation, and the cost per tonnes of recovered plastic. This number is found by:

$$C_{n,tonnes} = \frac{\text{Revenue - cost}}{RP} \qquad \textit{Eq. 6.6}$$

Where $C_{n,tonnes}$ is the net total cost in USD per tonnes, cost is the total cost of the entire operation in one year and RP is the recovery potential in tonnes. The “revenue” is based on the estimated value of 0.16 USD per kilogram, this number is only considering the value of the material and does not consider any external benefits yet. The next chapter will suggest a method to formulate the value of those external benefits. Additionally, it should be said that this cost calculation therefore only considers direct costs.

6.1.4 Results

The results for both case studies are given in Table 6.1 and Table 6.2.

	CASE STUDY OCEAN				
COST	investment cost	debt repayment (2 years)		4.0E+06	
	operational cost [$/year]	manning costs	58%	7.5E+05	
		stores and lubricants	17%	2.2E+05	
		repairs and maintenance	6%	7.8E+04	
		insurance	8%	1.1E+05	
		administration	10%	1.3E+05	
		total [$]			1293438
	Voyage costs [$/year]	fuel	85%	2.3E+06	
		port costs	15%	4.0E+05	
		canal dues	0%	0.0E+00	
		total [$]			2661029
		TOTAL COSTS [$/year]			7954467
BENEFIT	Recovery trajectory	width	0.60	[km]	
		delta V	0.20	[m/s]	
		area	3784.32	[km2]	
		concentration	0.05	[t/km2]	
		recovery rate	0.20	[-]	
		recovery potential	37.8	[t/year]	
		Ocean plastic value	160	[$/tonnes]	
		TOTAL REVENUE [$/year]			6054
COST BENEFIT	Netto [$/year]	total revenue	6.05E+03	[USD/y]	
		total cost	8.0E+06	[USD/y]	
		NET COST [$/YEAR]			7948413
		NET COST/PER TONNES [$/TONNES]			210068

Table 6.1 Direct cost and revenue for case study A: Ocean.

CASE STUDY RIVER

COST	investment cost	debt repayment (2 years)		1.0E+05	
	operational cost [$/year]	manning costs	58%	6.54E+04	
		stores and lubricants	17%	1.95E+04	
		repairs and maintenance	6%	6.84E+03	
		insurance	8%	9.51E+03	
		administration	10%	1.15E+04	
		total [$]			112661
	Voyage costs [$/year]	fuel	85%	1.2E+05	
		port costs	15%	2.1E+04	
		canal dues	0%	0	
		total [$]			138630
		TOTAL COSTS [$/year]			351292
BENEFIT	Recovery trajectory	width	0.01	[km]	
		delta V	2.57	[m/s]	
		area	811.18	[km2]	
		concentration	2.46	[t/km2]	
		recovery rate	0.42	[-]	
		recovery potential	841.8	[t/year]	
		Ocean plastic value	160	[$/tonnes]	
		TOTAL REVENUE [$/year]			134696
COST BENEFIT	Netto	total revenue	1.35E+05	[USD/y]	
		total cost	3.5E+05	[USD/y]	
		NET COST [$/YEAR]			216596
		NET COST/PER TONNES [$/TONNES]			257

Table 6.2 Direct cost and revenue for case study B: River.

6.2 CONVERGE: CASE STUDY CONCLUSIONS & RECOMMENDATIONS

The cases can be compared by looking at the direct cost compared versus the recovery potential, and net cost per recovered tonnes of ocean plastic versus recovery potential, for both see Figure 6.3. Both cases do not show any positive values for revenue, which means that in both cases it costs money to recover plastics. Especially for case Ocean (green) the costs are extremely high compared to the recovery potential, roughly 210.000 $ for one ton of recovered ocean plastic. It can be said that this is a very large investment for a relatively low positive impact. Case River (blue) demonstrates a higher impact for a lower cost of 257$ per ton, which is more desirable.

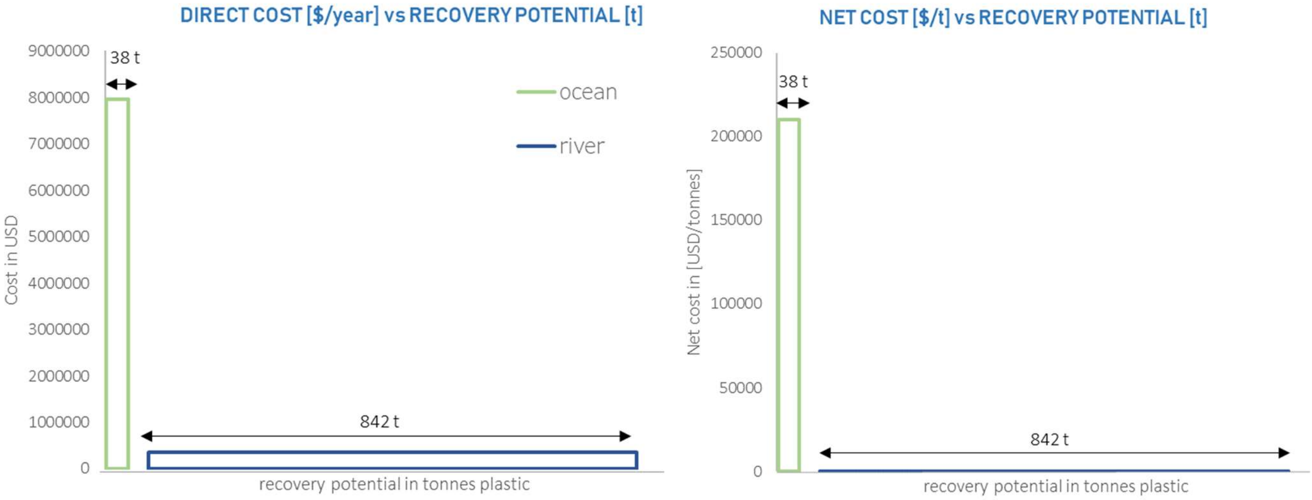


Figure 6.3 Result of business cases: on the left direct costs in USD/year (Y-axis) and recovery potential in tonnes of ocean plastic (X-axis), on the right net revenue per tonnes in USD/tonnes (Y-axis), and recovery potential (X-axis)

Other interesting relations resulting from this analysis are that:

- The area, or volume, that the technology can scan, is not the most important parameter for successful ocean plastic recovery. The ocean case had a greater reach than the river case, but as the figures below show, do not bring any significant advantages for the recovery potential.
- The most important parameter however is the concentration of plastics. The river case is so much more successful because of the much higher concentration of plastics.
- Even though the ocean case has an operability that is about 8 times higher than the river case (365 days with 24 hours versus 130 days with 8 hours), this still does not create any advantages for the ocean case.

Figure 6.4, Figure 6.5 and Figure 6.6 demonstrate the relations and effects of those mentioned variables. The three figures demonstrate the variation of the concentration of ocean plastic, total velocity and the recovery rate respectively, while the other variables remain identical as described in the direct cost calculation. For example, in the first figure only the concentration of ocean plastics is varied, and the width, delta V, area and recovery rate stay the same as they were for the previous calculation. The primary y-axis shows the recovery potential and the secondary y-axis the cost per recovered ton of ocean plastic. The green and blue circle-shaped indicators shows the current cost and recovery potential for both concepts. When looking at Figure 6.4, it is clear that the tangent of the cost per ton for the ocean case is still very steep at this particular point, meaning that a small increase in concentration (x-axis) can lead to a large reduction in cost per ton. Furthermore, it is interesting to see the increase in recovery potential by changing a variable that does not change any technicalities of the concept itself. Especially for the ocean-case it is striking to see the impact of concentration on the recovery potential (potentially up to 2700 tonnes a year), which is mainly due to the great area this technology can cover.

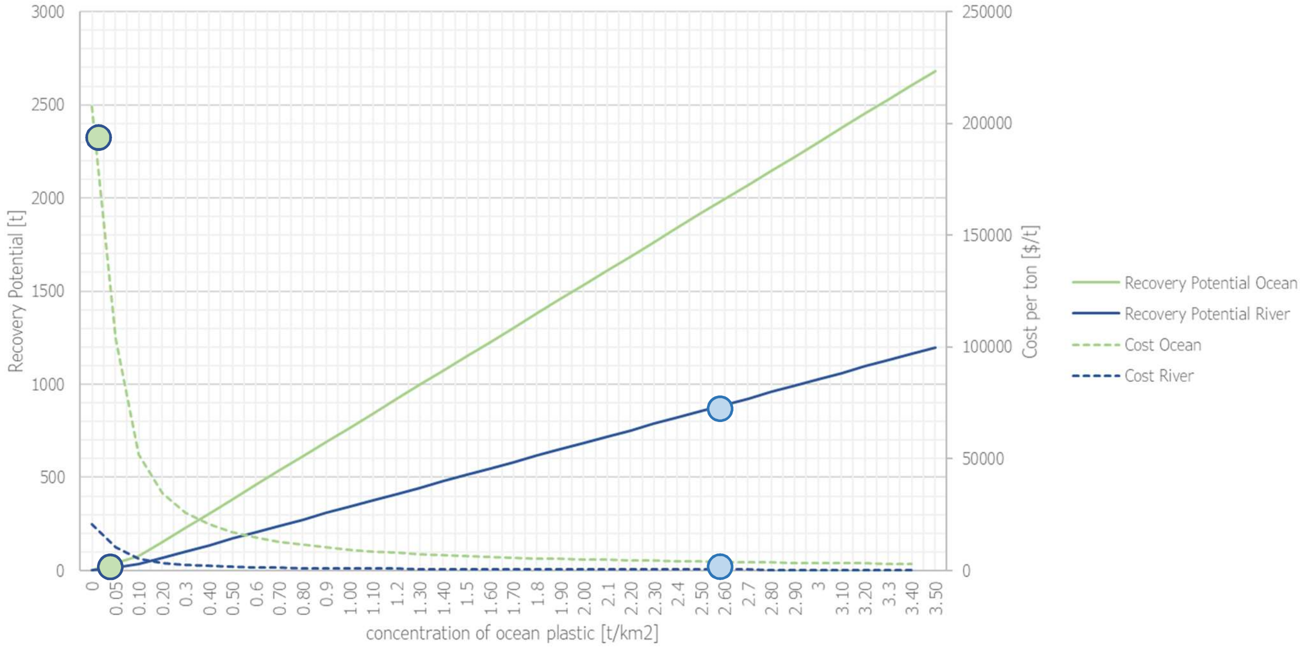


Figure 6.4 relation between the recovery potential, cost per tonnes and the variation on concentration of ocean plastic, for both ocean (green) and river (blue) cases

When looking at the variation of the total velocity, we can see a similar relation but less impactful. The recovery potential tends to diverge less when comparing the ocean case (up to 450 t) and river (800 t), since the tangent of the cost per tonnes curve is also less steep than the previous one. However, an increase in speed for the ocean case can still have an advantageous effect on the cost. For the river-case, an increase of velocity does not lead to any major advantages.

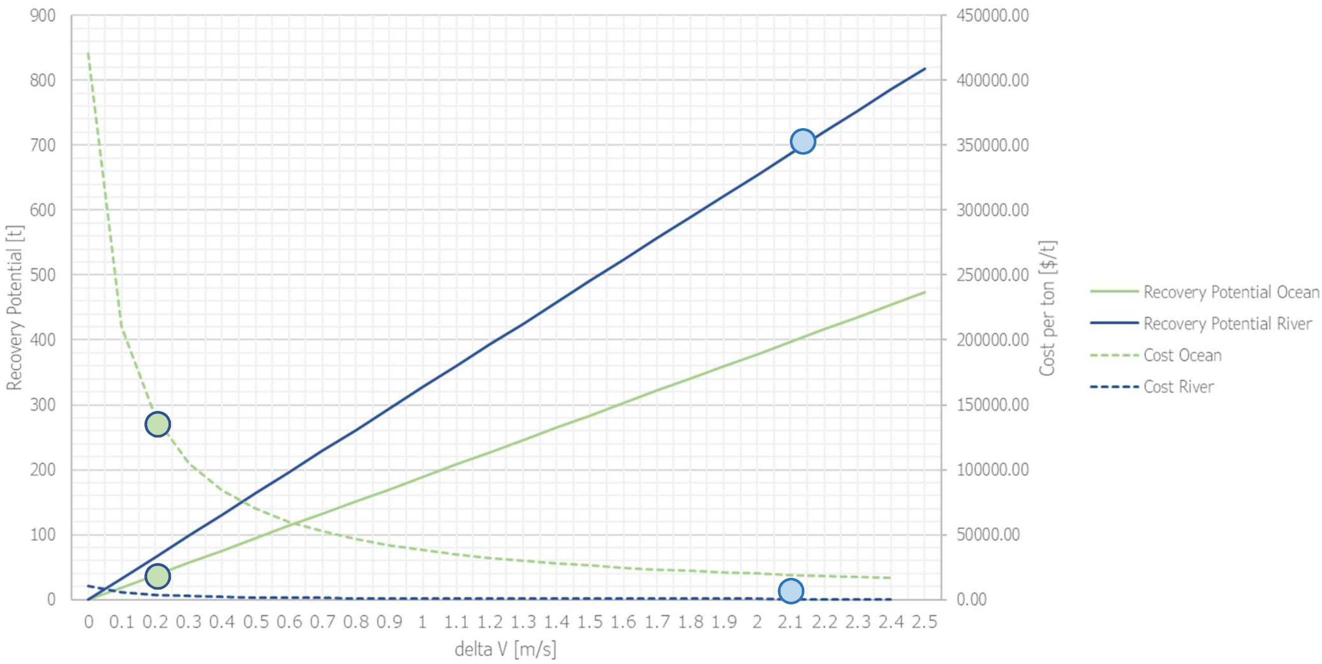


Figure 6.5 Relation between the recovery potential, cost per tonnes and the variation in delta V, for both ocean (green) and river (blue) cases

When looking at the influences of the recovery rate on the plastic recovery potential, we can find an interesting relationship. The recovery rate for the Ocean case was 0.20 and for the River case 0.42. There does not seem to be a strong reason to improve the recovery rate any further (by for example improving the operability of the system), since the tangent of the cost curves are both beyond there steepest tangents.

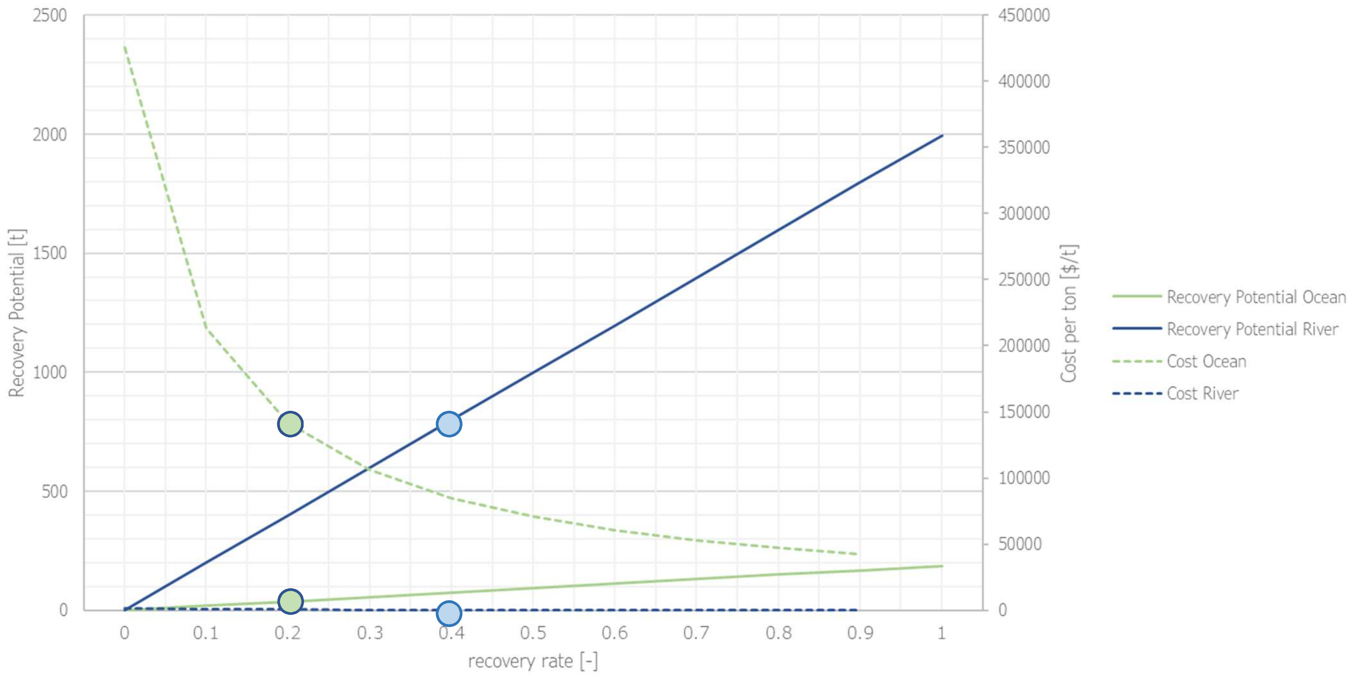


Figure 6.6 Relation between the recovery potential, cost per tonnes and the variation of the recovery rate for both ocean and river cases

Concluding, the river case is so successful (relatively to the ocean case) due to its target area with a high local concentration of plastics, high delta V and acceptable recovery rate. Also, the low investment cost (simple technology and utilizing existing vessels), low operational cost (small crew) and low voyage costs (short distances and small vessels) contribute to the good performance of this concept.

This model of direct costs has many variables and dependencies that were carefully determined, but rely on assumptions. The main assumptions one should be aware of:

- In this case the equations of Stopford have been used, combined with data from Drewry, which together offered the most reliable estimation of a non-existing industry today.
- Obviously, the used numbers are based on many assumptions and estimations, that affect the sensitivity of the outcome. However, even when different theories and sources are used, the outcome is unlikely to change. The River case proved to perform significantly better than the Ocean case that the used numbers are not much subjected to sensitivity.
- Both concepts rely on the use of fossil fuels and manned operations. The outcome will change when the investment costs, crew costs and/or voyage costs are reduced, which all may lead to interesting recommendations. For example, both cases utilize existing vessels sailing on fossil fuels, which are not just expensive, but also polluting. A potential future scenario is that there will be a transition to clean fuels. This will also affect the fuel cost in this calculation. Another potential scenario could be the transition to autonomous vessels, so the crew cost can be largely reduced. Both scenarios are interesting considerations for future studies.

PHASE 2/3 CONCLUSIONS & RECOMMENDATIONS

The aim of the second phase was to develop a multilateral methodology to provide guidance in design for ocean plastic recovery. Three methods were combined: a technology assessment, qualitative judgement and two business cases. It can be said that this first step, the technology assessment allowed us to collect and converge by using "brute force", e.g. a coarse filter assessing a first cost estimation and recovery potential. **ADDED VALUE:** This first step towards obtaining feasible and effective solutions identified several promising and diverse technologies, which were promoted to the second step of the methodology.

The qualitative judgement moved on from the "brute force" approach and assessed the business strategies of the favourable concepts in a qualitative manner. This was done by judging the concepts on criteria which together offer a thorough ethical investigation of the concepts. **ADDED VALUE:** This was an important addition to the methodology, since the research study pointed out that the integration between society, environment and technology is strongly expected to improve the overall effectiveness and feasibility. The qualitative judgement was based on several group discussions with experts, which is an absolute must when obtaining input for qualitative studies. The results were gathered in an assessment tool inspired by House of Quality and Harris Profile approaches, and refined for this specific purpose. The two favourable outcomes were promoted to the final two case studies.

The case studies are the third and last analysis of the methodology, and carefully quantified the direct cost of the two most favourable concepts. **ADDED VALUE:** This analysis not only identified the cost and the recovery potential, but also resulted in many interesting relations for ocean plastic recovery. The analysis showed that the velocity and recovery rate are not the most important parameters for successful ocean plastic recovery. Even though some concepts might have a greater areal coverage than other concepts, this does not necessarily make them more advantageous. The most important parameter however is the concentration of plastics.

The gained understanding of costs and benefits offer insights into the effectiveness of design, but does not necessarily make it realistically feasibly. To know whether the concepts are truly feasible, one must know if the cost and benefits are level with a willingness-to-pay. The next chapter will explore this economic indicator further.

When applying this methodology yourself, it is strongly recommended to:

- In the early stages of the methodology, to collect many technologies (both intended for this specific purpose, but also plausible technologies from other sectors), in order to start with a diverse and widespread database of potential solutions.
- In order to compare the technologies in a fair and impartial manner, the ratio between the cost/tonnes and the recovery potential offers the most reliable way of comparing technologies.
- The technology database is recommended to be updated on a regular basis, since it is a quickly changing industry. Currently, many interesting projects were found, but were not yet ready to be included into a database due to a lack of accessible data and/or concept level development.
- The group of experts for the qualitative judgement should be diverse as well to avoid any local bias, and the researcher should be aware of the fact these discussions can be quite cumbersome.
- And as for any other methodology, acknowledge that all models rely on simplifications and that the outcomes should therefore not be seen as the ultimate truth, but as guidance for well-structured decision-making towards effective design.

PHASE 3/3

This last phase formulates recommendations for ocean plastic recovery. During the project many research gaps and new relations were discovered, which are all documented for the sake of knowledge transfer and development. These recommendations cover topics for further scientific research, plastic recovery concepts and suggestions for key stakeholders.

But first, the willingness-to-pay – an additional financial source related to the indirect cost and indirect benefits of social business cases. Usually these indirect benefits are not immediately noticeable, but do improve matters in the long run and are incurred by the mitigation of accidents, the reduction of environmental damage and impacts on the quality of life. This is a decisive factor for many social business cases, since the indirect cost and benefits can have a significant impact. For example, many sectors may suffer from the risk of losing revenue. UNEP estimated a yearly cost of 13 billion USD for the total damage of marine litter to industries around the world. This number is a rough estimation, but what is does show, is that likely that the industry is willing to pay to reduce the risk of losing revenue.

ADDED VALUE: Eventually, this section shows how we can continue the pathway towards the most effective solutions for ocean plastic recovery.

7 THE THEORY OF THE WILLINGNESS-TO-PAY

The previous chapters assessed the effectiveness of the concepts. This was done by estimating the cost and estimating the extent it meets societal, environmental and technological needs. Although we have a quite clear idea of which concepts are the most effective, this does not necessarily mean they are feasible. **ADDED VALUE:** To make a judgement about the feasibility of the concepts, we bring in an extra financial indicator: the willingness-to-pay.

7.1 MODELLING THE WILLINGNESS-TO-PAY

The source for a willingness-to-pay is related to the indirect cost and indirect benefits of social business cases, and are usually not immediately noticeable, but do improve matters in the long run (Immers and Stada, 2007). These are additional benefits incurred by the mitigation of accidents, environmental damage and impacts on the quality of life. The willingness-to-pay can come from external parties, and can be voluntary or made mandatory (such as taxes). The willingness-to-pay is directly related to how many people, organizations or industries are willing to invest to reduce the chance of a negative outcome.

In the past, the theory of economic supply and demand curves has been used to estimate the willingness-to-pay. The supply curve was seen as *the marginal cost of damage*, and the demand would represent *the cost of mitigation*. Pollution was interpreted as a negative economic externality[15], since it may potentially do damage to other parties beyond those involved. After thorough investigation of the supply and demand theory, it was concluded that this method cannot do justice to the case of plastic reaching the oceans[16].

The *marginal cost of damage* (or the *marginal social cost*) however, still is a good financial indicator to consider when judging the feasibility of recovery concepts. The marginal social cost is a result of the risks for industries, environment and societies, estimated as a cost per tonnes or plastic. This factor is well-considered in modern approaches to assess the feasibility. Nowadays, the supply and demand curves are replaced by *marginal abatement cost curves (MACC),* (see Appendix 4 for an example of a mature MACC)*,* because of the following advantages:

- MACC allows comparison of concepts based on the net cost per tonnes and the recovery potential. As previously found in this research, these two parameters offer a fair way of comparing concepts.
- The MACC takes into account the marginal social cost and uses that as a benchmark for the willingness-to-pay: meaning that every concept that has a lower recovery cost per tonnes than the marginal social cost, is feasible. The effectiveness is then assessed by the recovery potential.

The subsequent paragraphs will discuss what needs to be in place to determine this marginal social cost, and eventually to develop a marginal abatement cost curve.

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[15] Externality: the effect of a market on someone or something that neither consents, nor is considered in the market exchange itself. An externality can be either positive or negative.

[16] The supply and demand curves cannot do justice to the case of plastic reaching the oceans, because:
The supply and demand curves assume that pollution can only be seen as a negative externality. The previous chapters have proved that this is only partially true. There are many benefits, both quantifiable and unquantifiable, that are not considered by this approach. The marginal cost and benefit curves rely on proportionate change when the amount of pollution is changing. Since we are talking about a *marginal cost,* in this case a *cost per tonnes,* this is also not necessarily true either. Furthermore, the theory of supply and demand curves state that the willingness-to-pay is defined by the *enclosed area of the supply and demand intersection plus the consumer surplus.* This makes sense for an ordinary business case, but this definition simply does not satisfy the willingness-to-pay for concepts designed for anthropogenic issues. Paragraph 7.3 will propose a way to determine the willingness-to-pay for these issues in particular. Most importantly, it is difficult to consider or compare different concepts in a supply and demand curve. Usually, these curves have only one function for the marginal benefit and will therefore not help when looking into the most effective and feasible solutions.

7.2 THE MARGINAL SOCIAL COST

In paragraph 2.3.1, the outcome of not acting at all was considered, reporting negative outcomes for wildlife, human health, and loss of income for industries such as shipping, fishing and tourism. If the pollution increases further by lack of changes, all these parties will experience increased suffering. This paragraph focusses on negative outcomes for shipping in particular, and briefly refers to other sectors as well. These negative outcomes are essential when estimating the marginal social cost. **ADDED VALUE:** The negative outcomes for shipping has not yet been investigated by other research.

7.2.1 Negative outcomes for the shipping industry

All flag state-registered vessels need to report in case of any marine casualties[17]. The database of Sea-web has been used to obtain reported casualties that were caused by floating objects, ropes and wires (*Casualty Search - Sea-web*, 2018). Figure 7.1 shows the number of marine casualties caused by floating objects, ropes and wires over time, where the blue line represents the total number of casualties, and the orange line the serious casualties[18]. The graph shows for both types of severities an increase over time. Important to mention is that this data is not limited to plastics only, but are a collection of all reported casualties caused by all types of marine litter.

Next to the severity of the casualties, it is important to determine the vessel types that had the highest occurrence of events. The majority of the casualties (both types) have taken place on-board of fishing vessels, and secondly, on general cargo vessels, see Figure 7.2. The geographical zones in which the events took place are plotted onto a 3D global map, see Figure 7.3. The height of the data bars depends on the amount of casualties that took place within a certain zone and uses the same color-coding for the two types of severity.

During this analysis, several assumptions and simplifications were made. Noteworthy is that:

- This analysis included all relevant casualties reported to Sea-Web. It is very likely that the casualties are underreported, and there is a large chance that in reality many more accidents have taken place.[19]
- This analysis includes all casualties caused by floating objects, ropes and wires that were reported to Sea-Web. This means the data is not limited to ocean plastics only. Marine litter and ocean plastic pollution originate from the same problem sources, which are mainly waste mismanagement on land, and to a smaller extent the waste mismanagement on-board of vessels.
- The mismanagement of waste is not the only reason for the increase of casualties. Other influencing factors are an increase of vessels and an increase of reporting casualties.
- This analysis only includes vessels that are registered under a flag and do not represent any local or minor vessels. This is another reason why the number of casualties used in this analysis might be an underestimation of reality.
- The geographical plot shows the zones as points to demonstrate the occurrence of events within a certain area. This visualization does not represent the actual location of the event.

[17] Definition casualty: an event, or a sequence of events, that degraded the system beyond acceptable limits but can be counteracted or controlled adequately by alternative means (Rausand, 2011).

[18] Definition serious casualty: an event, or a sequence of events, that resulted in death or injury or prevented performance of the intended mission (Rausand, 2011)

[19] Dr. ir.Rolf Skjong (chief scientist DNV GL) estimated that only 30% of casualties is reported to Sea-Web. This conversation was held on August 22nd at DNV GL Høvik, Norway.

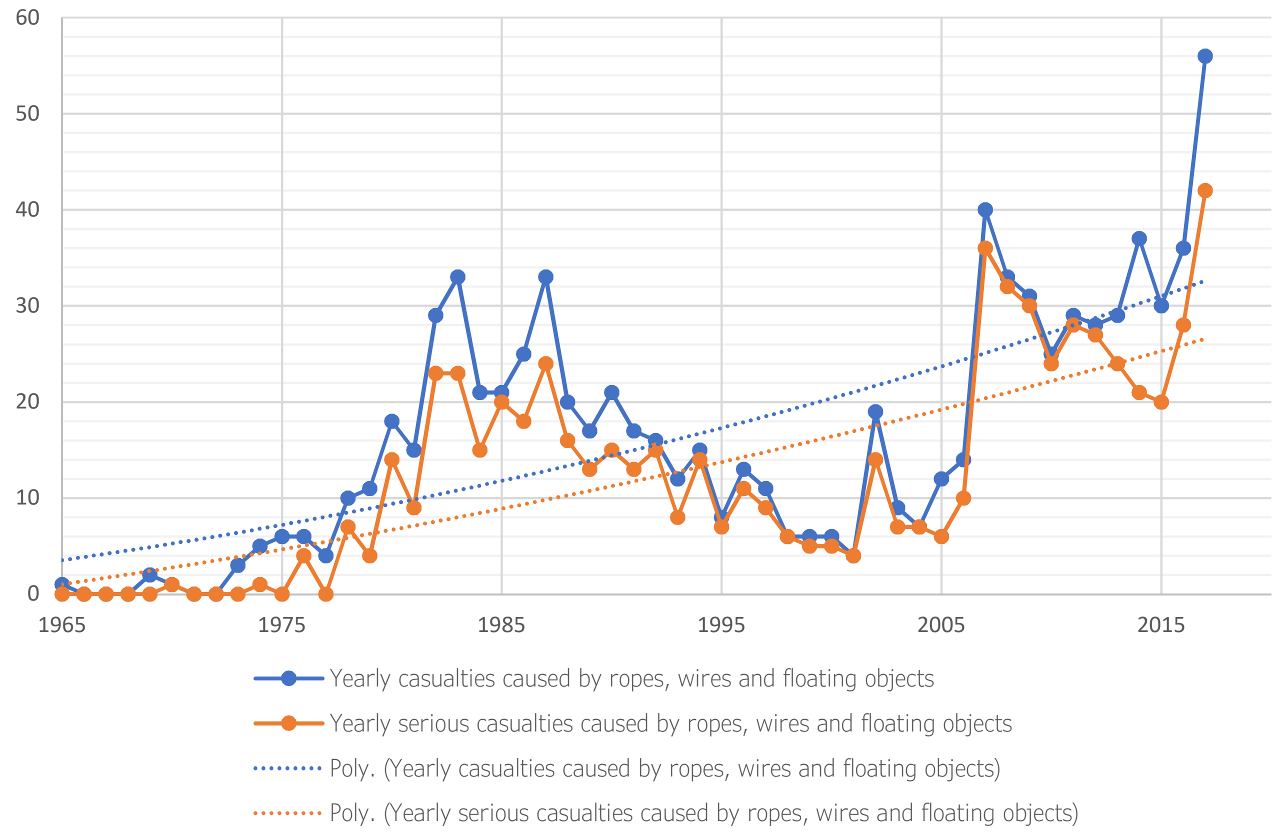

Figure 7.1 number of marine casualties (Y-axis) caused by floating objects, ropes and wires over time (X-axis). Data from (Casualty Search - Sea-web, 2018), ©Vera Terlouw

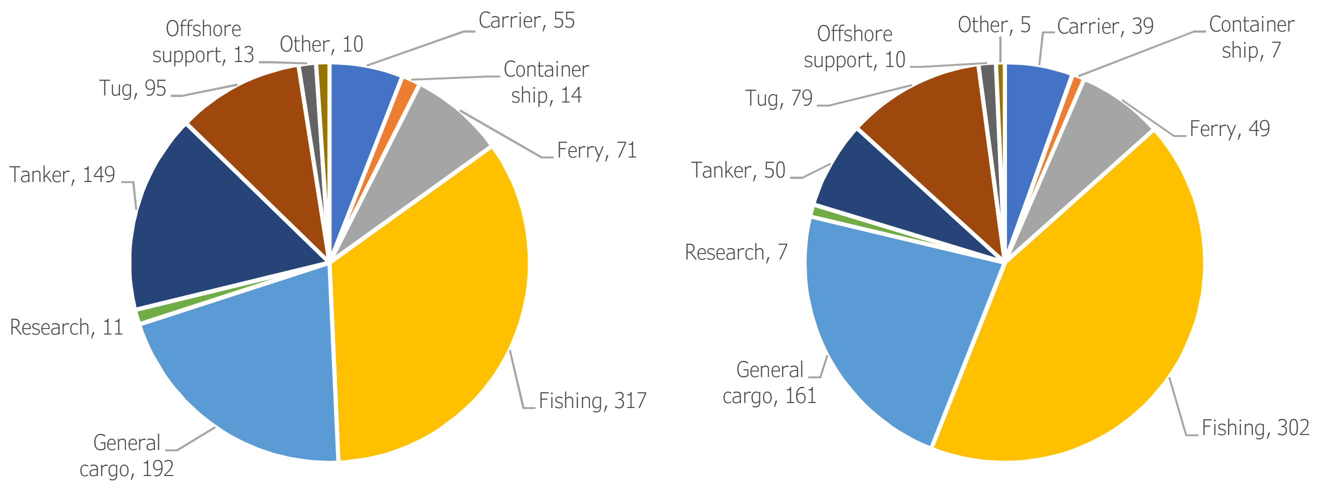

Figure 7.2 Marine casualties caused by floating objects, ropes and wires per vessel type. Left shows all casualties, right serious casualties only. Data from (Casualty Search - Sea-web, 2018), ©Vera Terlouw

Two casualty reports are attached to this report as examples, see Appendix 5 and 6. The indirect costs for shipping are a result from not being able to run the operation and repair (time and cost), and potentially loss of life. This revenue at risk is dependent on the severity of the casualty, vessel type, size, type of operation, land of origin, flag and location. Today's estimation for fishing vessels is between 17.000€ and 19.000€ per year average. For the Scottish fishing industry (where the study took place), the total cost is estimated to be between 11.7-13 million € every year. This is 5 % of their total annual revenue (Kühn, Rebolledo and van Franeker, 2015). The calculation used the average value of 1 hour fishing time as estimated by vessels surveyed.

For the shipping sector, the marginal cost is dependent on the frequency of hazardous events, and the severity of its consequences. The frequency can be compared to the traffic density at a certain location, which identifies the chance of a potential accident. Appendix 7 shows the traffic density maps for the areas of the two casualties described before. By doing so, an individual risk can be obtained and compared to the individual risk criterion that defines the intolerable and the broadly acceptable risk. These criteria are the limits to the area where cost-benefit may be applied. Intolerable risks must be reduced irrespectively over costs, where the risk should be reduced as long as the risk reduction is not disproportionate to the costs (Skjong, 2002). For a specific activity, an average Potential Loss of Life (PLL_A) may be based on the average fatality rate, combined with the economic value of the activity:

$$PLL_A = \left(\frac{\text{Number of occupational fatalities}}{\text{GNP}} \right) \cdot \text{economic value}$$ *Eq. 7.1*

This approach is officially accepted by the IMO and is often used to address maritime issues, and to propose new regulations. It is strongly recommended to continue this study, and more particularly:

- Minimizing the risk of underreporting
- Exclude all reports that are not related to marine litter (which were not correctly reported)
- Estimate the number of occupational fatalities
- Define boundaries for PLL criteria
- Study whether the current risk is within these boundaries, and if not, how much it costs to reduce the risk.

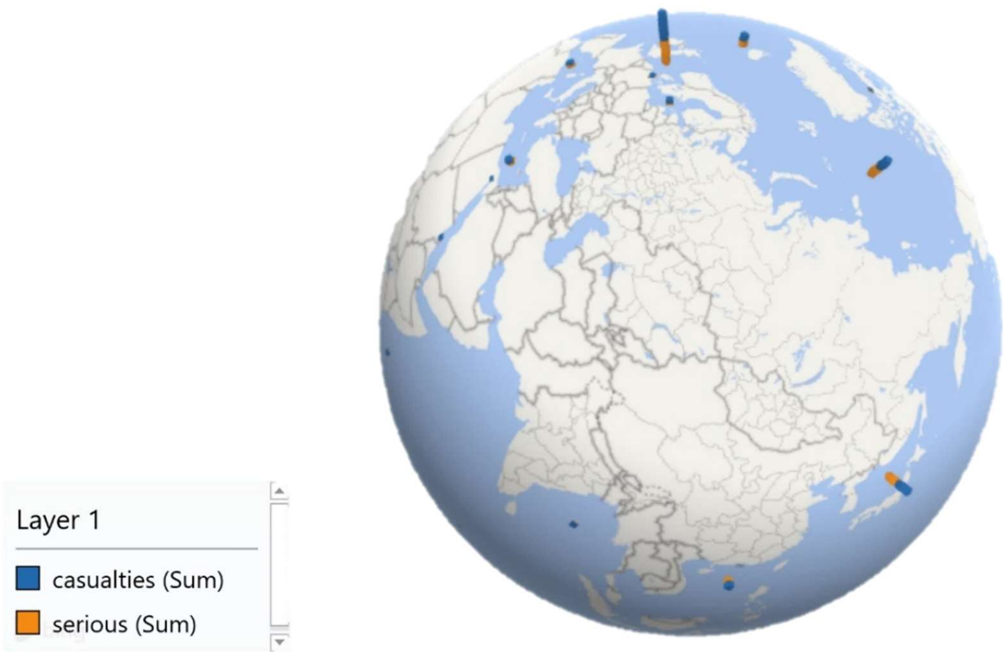

Figure 7.3 Impression of 3D map of reported casualties caused by floating objects, ropes and wires. Data from (Casualty Search - Sea-web, 2018), ©Vera Terlouw

7.2.2 Negative outcomes for other sectors

Shipping is not the only sector that is affected and the revenue is at risk. Figure 7.4 was published by UNEP and shows the natural capital cost per service year, compared to the percentage of risk at revenue due to plastic pollution. This same report stated that the total damage to industries around the world is estimated to be 13 billion USD (Sireyjol Trucost *et al.*, 2014). These findings can be solidified by (Kühn, Rebolledo and van Franeker, 2015), in which they sum up the financial implications for shipping, fisheries, aquaculture, agriculture, tourism and human health. For tourism for example, they have obtained a direct correlation between increasing amounts of litter and decreasing revenue. Global trends have not been obtained yet, but many local and national studies can confirm the loss of revenue.

For example, South-Korea has reported to have lost expenditure after a significant decrease in visitors compared to the average (500.000 visitors fewer), after an extreme wash of marine litter onto the beaches in 2014, with an estimated lost revenue between 23-29 million €. In Orange County (California, USA) monitored 31 beaches and its revenue, and saw a 40 million € in additional revenue after decreasing the marine litter with 75% (Kühn, Rebolledo and van Franeker, 2015). It goes without saying that there are many other contributors to this decrease in income than just plastics reaching the ocean. The example of South-Korea was reported right after the country was hit by a typhoon and which caused a national emergency state, which surely affects the tourism sector as well. It does show the difficulty of isolating the financial impact of just plastic pollution.

Although many scientists confirm the negative effects on human health, no one has been able to identify the risk by frequency and consequence yet. A similar approach as described in the previous paragraph for shipping, can be applied to society. The frequencies of the consequences need to be researched further so a chance of a negative outcome can be developed. From there on, it should be assessed if this risk is within the acceptable boundaries, and how much can be invested to reduce the risk if necessary. So far, no study approached this issue in such a manner.

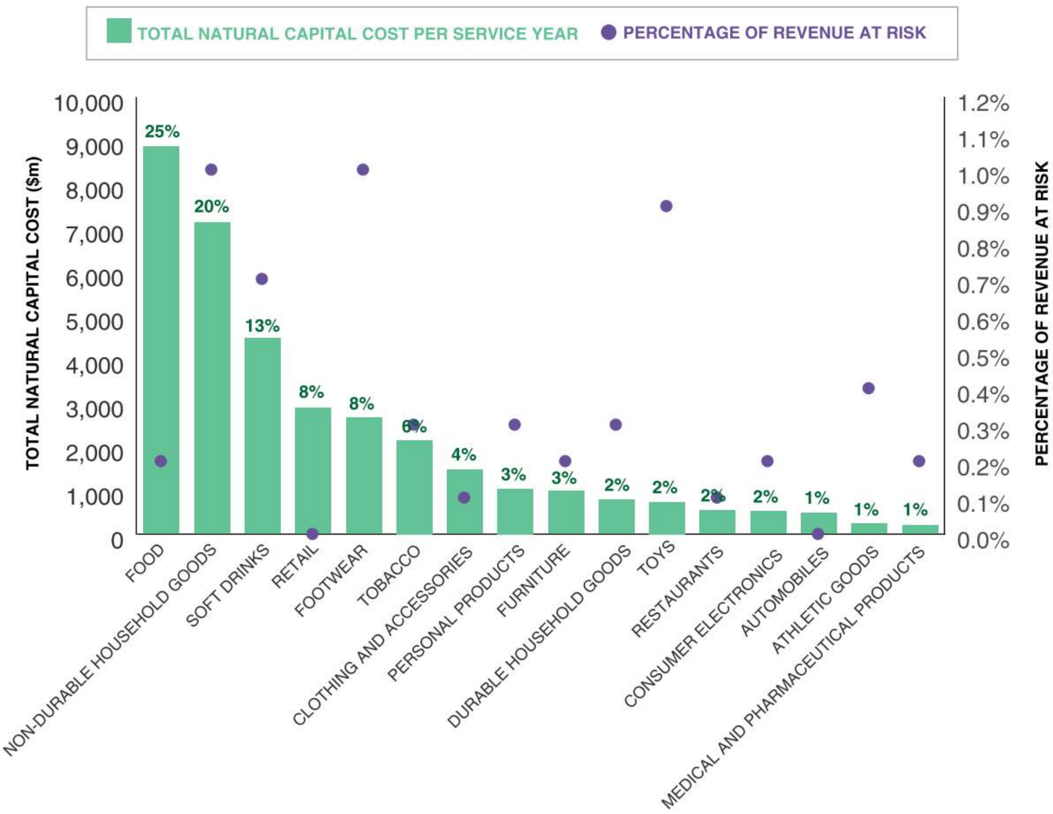

Figure 7.4 total natural capital cost ($) and revenue at risk (natural capital intensity) per sector, normalized by service year, courtesy of (Sireyjol Trucost *et al.*, 2014).

7.3 THE MARGINAL ABATEMENT COST CURVE (MACC)

As mentioned in paragraph 7.1 the recommended method for balancing the cost of abatement, marginal social cost and willingness-to-pay, would be a Marginal Abatement Cost Curve. Figure 7.5 shows a preliminary version of the MACC for the two favourable concepts of this research. The y-axis is the net cost per tonnes [USD/tonnes] to recover one ton of plastic by a specific concept. Again, this net cost is a result of the total cost of the operation, minus the value of the material that has been recovered. A high value on the y-axis would result in a high cost. A negative value would be a negative cost, meaning that this concept would generate income. The width of the concept represents the impact measured in recovery potential (tonnes).

For now, both concepts have positive cost value, hence it still costs money to recover plastics. However, this is not necessarily unacceptable. As seen in the previous paragraphs, the willingness-to-pay represents the value people are willing to put in to reduce the chances of a negative outcome (risk of accidents, health risks, revenue at risk, etc) and increase their chances of a potential benefit. This willingness-to-pay is directly dependent on the marginal social cost curve, also expressed in cost per tonnes (represented by the red dashed line in the figure). The area below this line is the willingness-to-pay. The estimation of the value of the marginal cost is a research field on its own, since it considers many different societal and environmental factors. When applying such a marginal social cost, one should also be aware of the cultural impact on this particular value. Many of these cultural, societal and environmental factors are still unknown, see for further information the recommendations for future research (paragraph 8.3.1).

In Figure 7.5 the marginal social cost curve has been valued as 45 $/tonnes. It should be mentioned that this is a very first educated guess of this value, based on the findings of the previous paragraph, and can be seen as illustrative only.

Clearly, this MACC approach is intended as a basis for future work. For now, only two concepts have been examined and put into this MACC, and neither of them meet the requirement of the marginal social cost. In future, many more concepts may be included, including the ones that actually fit below the marginal cost curve and are in balance with the willingness-to-pay.

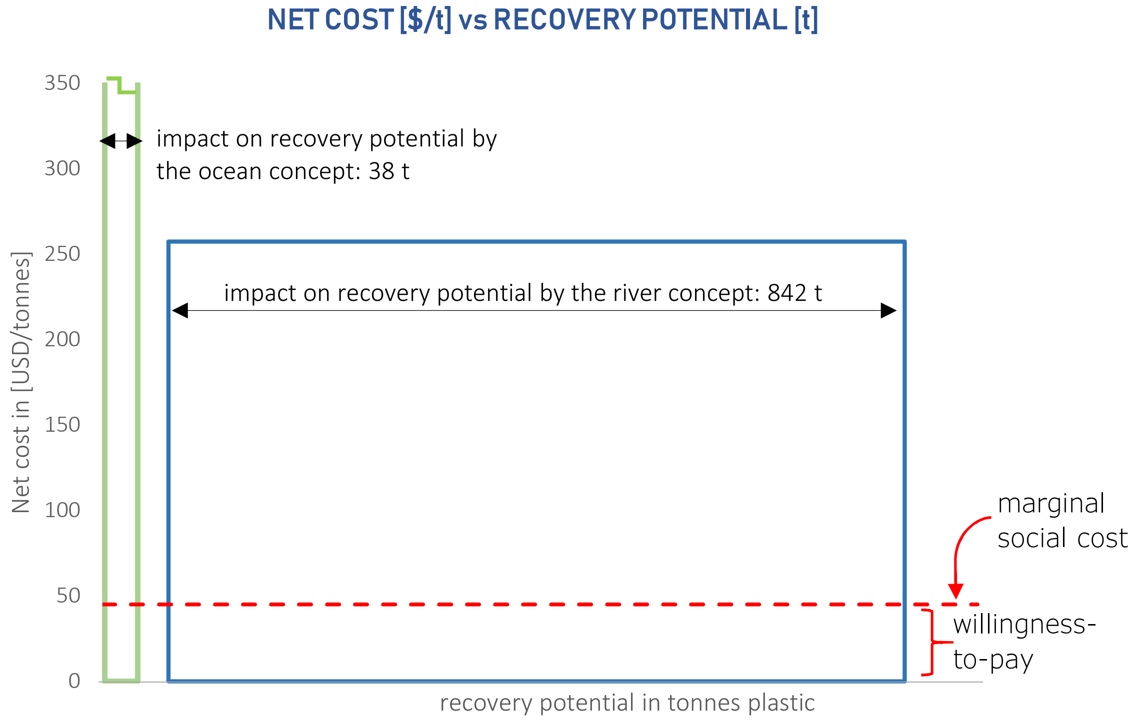

Figure 7.5 Preliminary MACC for plastic recovery solutions

7.4 INTERMEDIATE CONCLUSION & RECOMMENDATIONS

The financial gap between the estimated revenue and cost, can theoretically be closed by the willingness-to-pay. This financial indicator is a result of what the society and industry are willing to pay to reduce any further damage. For the shipping industry in particular, it was found that marine litter is creating hazardous events, with a significant increase over the last 15 years.

The willingness-to-pay is directly dependent on the marginal social cost. To determine the value of this marginal social cost, a lot of new research needs to take place. **ADDED VALUE:** Although there is still a lot of investigation to be done, it seems highly likely that there is a marginal social cost, and therefore, also a willingness-to-pay. Many industries are already losing revenue, the environment is suffering and human life is directly at risk. Hopefully, researching the willingness-to-pay and balancing this value with the cost of plastic recovery, will result in a strong willingness to act. The marginal abatement cost curve has the ability to prove that there are effective and feasible ways to improve matters.

Additionally, the theory of willingness-to-pay can be applied to the case studies in the last part of the methodology. Since the parameter studies (Figure 6.4, Figure 6.5 and Figure 6.6) use the same definition of cost per tonnes, the marginal cost of damage can be combined with the curves for net cost and recovery potential. This will be useful when looking for individual improvements of specific concepts.

This chapter led to a substantial amount of research recommendations. These are discussed in paragraph 8.3.1, starting on page 76.

8 FINAL CONCLUSION & RECOMMENDATIONS

This chapter concludes the project and suggests recommendations for the continuation of this pathway towards the most effective solutions for ocean plastic recovery.

8.1 FINAL CONCLUSION

Plastic reaching the ocean – a complex problem that requires many different types of solutions, both on land and offshore, global cooperation and participation. This thesis may only concentrate on one specific type of solutions, but it can be concluded that for this specific area, we may be a step closer in turning the problem into value.

From the first phase of this project it can be concluded that the pathway towards effective solutions, needs to be supported by a robust foundation of research. One of the striking findings of this part of the research was that currently, an understanding of the totality of the problem is lacking. A Formal Safety Assessment might be a suitable risk-based approach where the hazards, risks and control options can be organised in a structured manner. The research confirmed the urge of improving matters: if nothing would happen at all, if no barriers would be put into place, the amount of plastic reaching the ocean will continue to build up, resulting in many more consequences than just the pollution itself. Direct consequences can be found when the plastics are broken down into micro-plastics and enter the food chain. Toxification and starvation by ingestion and inhalation are some of the consequences that are already noticeable. The macro-plastics have also resulted in major hazardous events, such as obstruction and breakdown of (shipping) equipment, causing damage to vessels, human injuries and fatalities.

The main conclusion of the first phase was captured in the Strategic Solution Space, a new summary of the most essential qualitative factors contributing to any solution intended for high impact. Although most of these qualitative factors result in indirect benefits which might be difficult to quantify, they should nevertheless be considered. As for any type of anthropogenic problem, without acting, the long-term negative consequences will eventually outweigh the direct short-term saving of cost that are currently saved by not acting at all. Therefore, it is important to act and to consider those long-term consequences and benefits, even when only looking at short-term solutions. This Strategic Solution Space provides an inclusion of both direct and indirect benefits by connecting technology, environment and society.

Logically, when investigating solutions, one should look further than only the direct performances. By using a multilateral methodology as described in Phase 2, both the direct and indirect costs and benefits are considered. The main advantages of this methodology turned out to be the ability to compare concepts multilaterally, and by knowing how to increase the individual effectiveness of each of the concepts. Some of the parameters, such as the plastic concentration, are way more impactful than others, which is obviously nice to be aware of when designing for the biggest impact. Furthermore, it was found that these solutions should not only be compared to one another, but also to a long-term scenario where no one acts at all. Appropriate tools for this comparison, are the trajectory study and the source-sink model. These two tools combined are a new starting point for future research. Overall, during Phase 2 many interesting relations and recommendations came to light.

Besides knowing which solution is the most effective, it is important to consider its feasibility. As described in the first part of Phase 3, the Marginal Abatement Cost Curve lays the foundation for feasibility assessment by balancing societal benefit and cost of abatement. The main MACC parameters, the marginal social cost and the willingness-to-pay, turned out to be incredibly challenging to estimate, due to many influencing factors. This should however not result in withholding from investigation: it is quite certain that there is a societal cost of damage and therefore also a willingness-to-pay; many industries are already losing revenue, the environment is suffering and human life is at risk. Avoidance and reduction of those negative outcomes will result in the ultimate incentive to act.

Summarizing, this project has the ability to offer guidance in the design processes for ocean plastic recovery solutions. The outcome of the project obviously resulted in many recommendations and discovery of many new questions, but it also helped to effectively design with the multilateral approach that offered a balance between technological, societal and environmental ethics. The stepwise convergence of concepts during the methodology's progress enables the user to reject the less effective concepts and focus on the concepts with the highest potential - so the time is spent wisely.

8.2 DISCUSSION

This project connected today's problem status, discussed potential barriers, proposed the application of trajectory studies and assessed concepts in a step-wise manner. For all of these parts, models were developed. As for any model development, simplifications and assumptions were made along the way. It should be mentioned that:

- The used concentrations of ocean plastics are based on today's scientific estimations of Lebreton and Jambeck. However, these publications bring up questions about the reliability of the actual data, since this research field is still in its early days. Reliability and verification of data are two of the main issues that were encountered during this project.
- Quite some assumptions were due to the lack of accessible information about concepts. Many of the concept owners are reluctant to share technical reasons. Especially for the first part of the methodology, the technology screening, this lead to quite some challenges. There was a large variation in accessible data and development of the concepts, which lead to the fact that the technology screening selects concepts not only on recovery potential, but also maturity of design as an inevitable selection criterion.
- The cost-analysis is aimed to focus on the direct cost only. Throughout the project it became clear that this particular issue does not only affect the immediate users or operators of the concept. Many others are influenced too. Operators pass on their benefit to third parties and spread the benefit throughout society. These indirect effects are not considered in the cost analysis in order to avoid any double counting of costs and benefits. This obviously is a simplification of the actual situation. To minimize its effects, the indirect benefits are well-considered in the second step of the methodology (qualitative judgement), but just not quantified in any monetary value for this specific reason of potentially double counting.
- For social business cases it is strongly recommended to assess them on the long term. Since the development of this upcoming market is still in an early stage, this was undoable. The model assesses the case studies for the first two years of operation, with a focus on operational cost.
- For the accident analysis the used cases included reported accidents caused by ropes, wires and floating objects. There is no accessible database of accidents caused by plastics only. However, the reported accidents were mostly caused by marine litter. The assumption here was that marine litter and ocean plastics are relatable issues and both report an urge for restoration of the ocean's health, and reducing human risks.

8.3 FUTURE RECOMMENDATIONS

These recommendations are a collection of the knowledge gaps that I found during the development of this thesis. The majority goes beyond the scope of this thesis, but do address some of the biggest needs within the challenge of ocean pollution and sustainable ocean utilization. This chapter is organized by three sections: one part covers the recommended scientific research, the other part covers recommendations for key stakeholders (including DNV GL), and the last part is a recommendation for solutions.

8.3.1 Recommendations for Further Research

During the development of this thesis, I have identified several topics for future research. These are the most important ones:

- Properties of (micro-)plastics, and long-term changes to properties. This includes, but is not limited to:
  - Longer term degradation rate. Most of the research only covers degradation of plastics for the duration of its consumer life expectancy. It is not known how long it takes until plastics break down into monomers. Neither do we know when plastic polymers are "fully degraded", and when they are fully degraded, if they still can do any harm to life.
  - Closely connected to the long term degradation rate, is the toxicity of (micro-)plastics. The plastic particles are suspected to "stick" to other particles, including toxic ones.
  - Long term human health risks. Today, scientists question whether (micro-)plastics are harmful to humans. Ingestion and inhalation of (micro-)plastics are considered as possibly harmful, but a robust argumentation is lacking. For example, it would be incredibly interesting to study the effects on the physical condition of people who have been working in the plastic production industry. These people have been exposed to high concentrations for a long time, and would be an ideal focus group for such studies.
- It is recommended to research how much plastic should be reduced each year to reduce the accumulated amount of ocean plastic in the long-term (as was described in the plastic recovery trajectory study, paragraph 3.1.2). This is closely connected to find an acceptable reduction of the pollution rate.
- Verification and validation of the most important resources, such as Jambeck and Lebreton. Their results are widely used and are accepted as today's truth, however there is no research confirming the findings of Jambeck nor Lebreton. One resource in particular, and that is the publications about the ten rivers as largest contributors to marine litter (Lebreton *et al.*, 2017). The published data is mostly based on numerical models, which are not sufficiently validated with on-site measurements. Another uncertainty is caused by errata in the publication itself. During my study, I found that the average estimated mass input is lower than the estimated lower bound, which is from a mathematical standpoint impossible[20]. A lot of research is dependent on this particular publication, so I would like to suggest to validate and verify its outcomes, and by doing so, increase the robustness of these widely used sources.
- From a risk-perspective, I would recommend to study an estimation of the lower and upper bound of the risk for loss of life, and an assessment of the current risk. From there on, the risk can be reduced by a proportionate investment (the willingness-to-pay). Obviously, this should not be limited to the data from the shipping industry only.
- Furthermore, I would be recommend to research the topic of designing for sustainable ocean utilization (an upcoming industry), and what needs to be in place to facilitate growth. For example, many regulations are a result of previous market and industry needs that actually discourage growth of today's industries. For example, when looking at ocean plastic recovery, some maritime and national regulations do not allow the import of plastics originating from international waters, or ask to pay import duties. This obviously does not make any sense when

[20] This erratum has been reported to The Ocean Cleanup Foundation (sponsor of Lebreton) on August 20, 2018. No explanation or answer has been received yet.

attempting to solve anthropogenic issues or promoting growth of those businesses, and needs acknowledgement and change. Another big need is a new regulation for areas that used to have a low traffic density, but that are expected to increase significantly. For example, the ocean gyres can be utilized for ocean plastic recovery, but the low currents and reasonably low sea states could also offer a great area for ocean energy harvesting. Currently, there are no clear regulations for those technologies, or the interference of different purposes in the same area.

- Additionally, there is a lack of reliable and accessible measurement tools. When marine litter is collected, there is no smart of efficient way of studying the "catch". Nowadays, most researchers rely on many hours of labour-intensive work and have to sort plastics piece by piece. In the meantime, the on-land plastic recycling industry (at least in the Netherlands and Norway) seems to be many steps ahead when it comes to sorting plastics. It would be recommended to use those sorting techniques and apply them in a different setting as well to improve the effectiveness of ocean-based plastic research.
- Another recommendation is to continue with the application and improvement of the methodology, preferably open-source so many people have access to the same data and its findings. The parts that I would suggest to continue to work on, would be:
    - The marginal abatement cost curve, especially a method to determine the marginal social cost. This indicator is dependent on many other factors, and also differ for each country, nation or region. Although the marginal social cost may vary, a method to estimate might still be applicable for all.
    - The collection of technologies and concepts should be accessible to developers of solutions (in all stages of design). The reason being that cooperation is essential when formulating, assessing and challenging the state-of-the-art of an industry. When developers can freely access and contribute, they would be able to test their solutions, which will improve the overall effectiveness and feasibility.
    - Linked to the previous argument, would be to test and improve the Strategic Solution Space (paragraph 2.5.1) and the corresponding criteria (paragraph 5.1).
    - Furthermore, I would recommend to use this methodology for educational programs with the learning goal to educate people in sustainable ocean utilization, and on the contrary, ocean pollution. When this methodology could be applied in an open-source manner, many students can contribute by developing own plastic recovery techniques, and immediately assess them with the three steps of the methodology. Creating and sharing new ideas will hopefully create better ownership of the problem as well, and make the students feel that they can truly contribute.
- As a last recommendation I would like to come back to the quote on one of the first pages of this report (there is only one type of waste – the waste of time). It is of great importance to continue with scientific research, but not use it as a reason to postpone the development of solutions. There is still a lot to be discovered, but this should not be used as an excuse to prevent from acting. As this study demonstrated, the investigation and assessment of solutions actually pointed out some of the big needs of scientific research. Thinking towards solutions will give both purpose and guidance to research and ultimately, save time so we can tackle this problem now we still can.

8.3.2 Recommendations for key stakeholders

Based on the findings during this project, I would like to suggest several recommendations for some key stakeholders. Starting with the IMO, who has Marine Litter as one of today's priorities on its agenda. At the moment, their main resources are the UNEP and GESAMP reports, which focus on the sources and potential fates of (micro-)plastics, which do not provide a sufficient connection between causes, hazards, hazardous events, consequences and barriers.

According to my opinion, there are three things the IMO could possibly focus on:

- Invest in research: Continue with the casualty research (paragraph 7.2.1) and investigate the risks for the shipping industry in particular. When knowing more about the risk, the acceptability of the risk can be determined, which may potentially result in an appropriate roadmap for the shipping industry.
- Promote and support plastic recovery initiatives: Invite (maritime) initiatives to share their insights and needs. This knowledge may be useful for recommendations for amendments to marine litter regulations.
- Include incentives for shipping in IMO regulations: Plastic recovery and on-board collection should be awarded, and not the other way around. The same for data collection, the IMO could promote ocean plastic data collection, since the current research is not robust enough. This would be a great way for the shipping industry to contribute in solving this problem.

For the United Nations, especially the UNEP and UNOPS I would advise to:

- Invest in education: As mentioned in the research recommendations, education will be key to changing habits. I would recommend to promote educational awareness programs that focus on solutions, both on the preventive and reactive side of the matter.
- Promote a global ocean utilization platform: Global cooperation and ability to share knowledge is crucial when time is running out. The UN could offer this global connection and support knowledge transfer, and create a global forward-thinking solution space.
- Promote national and local initiatives: As was found in this research, many cultural and societal differences make it difficult to find one solution that solves it all. However, sustainable and durable solutions should be sought locally and nationally to correspond and create ownership among the local society and support their quality of life.
- Facilitate to improve global waste infrastructure: On the long term, it is important that the source of pollution must stop. The global waste infrastructure does not satisfy tomorrow's needs. The UN can possibly offer support towards solving this incredibly difficult matter.

For DNV GL in particular, I would like to advisee how they could position themselves in this new market, by aiming to get recognition as the 'ocean plastic recovery clearing house' (Figure 8.1). In order to get there, I would like to suggest to participate in the following tasks:

- *Collect and facilitate reliable sources of research*. Many of the mostly used sources need verification and validation. DNV GL could use their Veracity platform to collect the available research in an objective manner, and initiate and support topics for further research. It can be advantageous for many companies and organizations to know what kind of information to use, and which ones to leave.
- *Invest in the power of prototyping* (inspire others by starting to solve). DNV GL can demonstrate the 'best practices' or best concepts in order to inspire the industry, and to show their positive, forward-thinking and responsible business approach.
- *Reward good initiatives*. Good initiatives should be promoted and rewarded for being an example. This could potentially take shape as student design competitions, certificates, publications, DNV GL quality marks, etc.
- *Connect with universities and support sustainable ocean utilization and pollution awareness programs*. Long term improvements will be made by well-educated future engineers. Investing in their education will convey how to utilize the oceans in a durable fashion.
- *Provide design decision-support to industry towards the most feasible and effective solutions.* Methodologies as described by this thesis can potentially function as a support tool when designing for high impact. DNV GL can take a consultancy role in such design processes.
- *Make all knowledge accessible* and have an open character towards the IMO and the UN for future improvements. Vital values of a reliable clearing house should be transparency and openness to knowledge transfer.

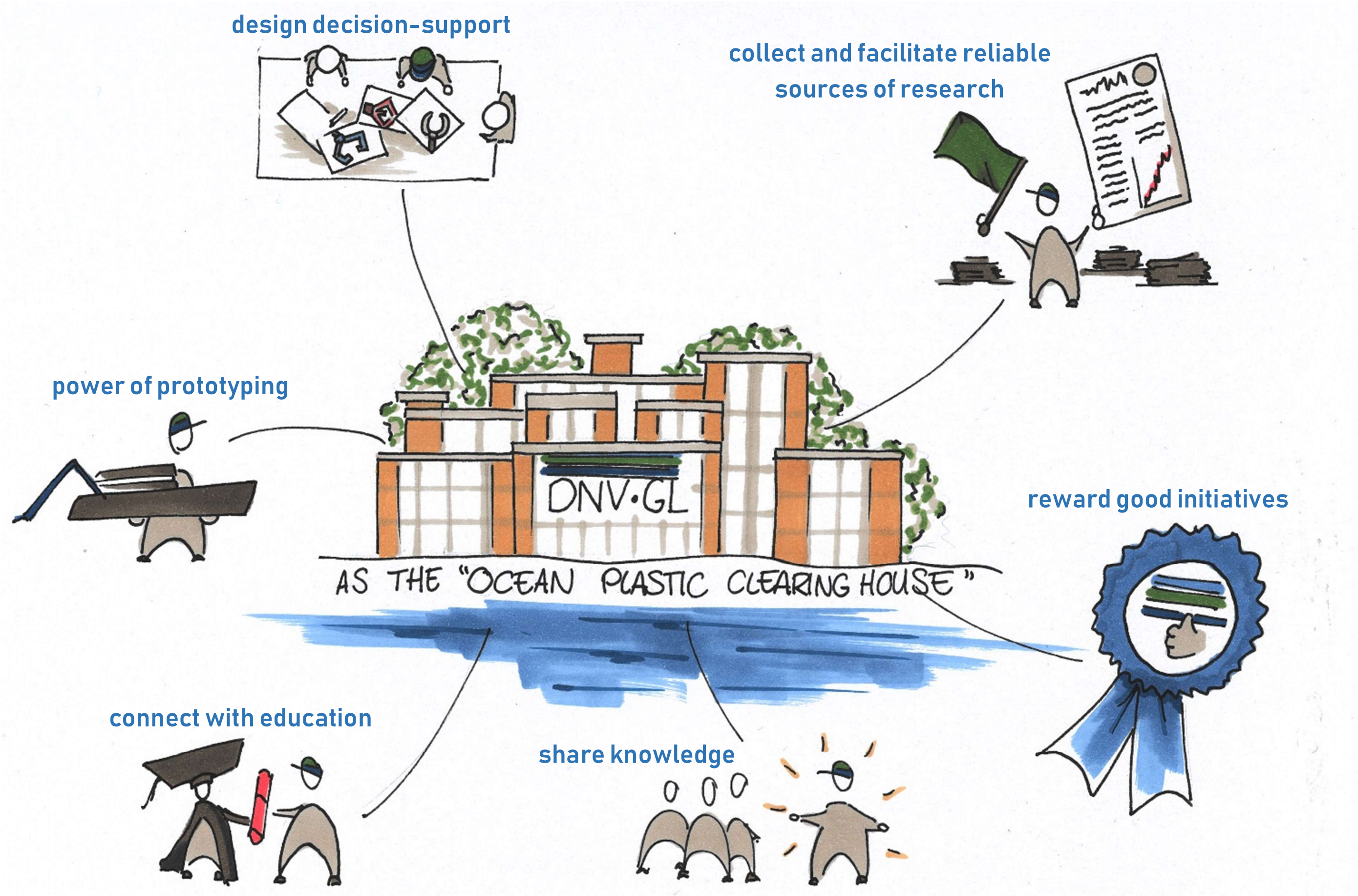

Figure 8.1 Illustration for DNV GL recommendation: get recognition as the ocean plastic recovery clearing house

8.3.3 Recommendations for Solutions

Developing this methodology gave many new ideas and insights for new concepts. This paragraph briefly sums up future steps for the two most favourable concepts in this report; the boom and the trawler. The aim is to fully use the potential of the Strategic Solution Space, and by doing so, design for the highest impact. When looking back at the findings from the second stage of the methodology, the qualitative judgement, we could combine the ratings of the boom (ocean) and trawler (river) into the following figure (green: ocean, blue: river, red: combined):

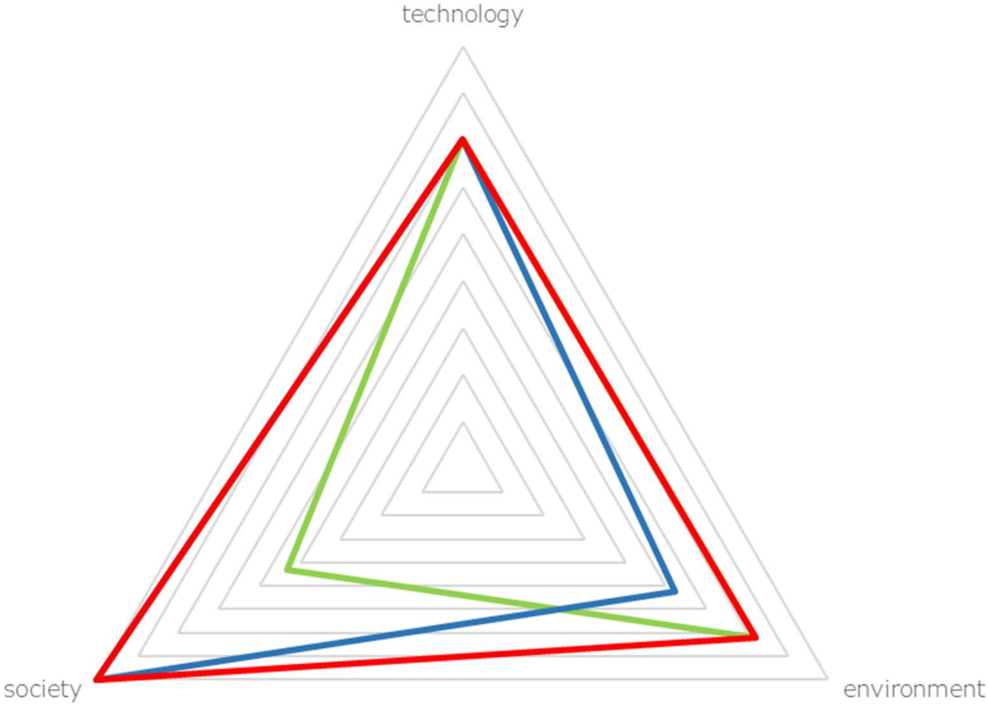

Figure 8.2 Recommendation for solutions: the best ratings combined (green: ocean, blue: river, red: combined)

To maximise such an area, the strengths of the two concepts may be combined. The strengths of the two concepts were:

- Societal connection of a river-based solution. It was close to shore, which made it easier to connect with local industries.
- The coverage of the boom structure, it was able to screen a large area for plastics.
- The bio-friendly design of the boom structure, since it is not quickly moving and fish has the opportunity to escape.

Opportunities for improvement are:

- Moving the location of the boom to high-concentration areas, making it compatible with rivers and coastal environments.
- Increase the weather window and improve the redundancy in case of breakdown of parts.
- Decrease human risk, but without excluding human involvement
- Abandon the use of fossil fuels and use clean energy instead (wind, wave, solar etc.)
- Use booms with skirts over manta trawls to improve bio-friendly design.
- Improve collection from boom to shore and treatment afterwards.
- Aim for areas with low employment rate and offer a sustainable business model (like a Bottom of the Pyramid project).

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ATTACHMENTS

A

APPENDIX 1: GRADUATION WORKPLAN

PLASTIC REACHING THE OCEANS – TURNING THE PROBLEM INTO VALUE

Student	Vera Corine Terlouw
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Master	Marine Technology SDPO, Shipping Management and Ship Design
Date	06/02/2018

INTRODUCTION

Marine life is facing irreparable damage from the millions of tonnes of plastic waste which end up in the ocean each year, the United Nations has warned. According to a scientific study, 4.8 to 12.7 million metric tonnes of plastic currently end up in the ocean every year (Jenna R. Jambeck, 2015). Most plastics do not bio-degrade but are broken down into smaller pieces, accumulating in ocean sediments and entering the food web. This type of pollution is disturbing ocean ecosystems and resulting in an increasing health risk for humans (DNV GL AS, 2016).

Among others, the International Maritime Organization (IMO) has been taking action to address the problem, including regulating the discharge of garbage from ships, but also supporting research work. The IMO has labelled marine litter as one of their 'in focus' problems, candidly describing the extend of the problem, and encouraging organizations, companies and general public to take responsibility (International Maritime Organization, 2017).

Tackling marine plastic pollution requires some original solutions. As it is a cross-border phenomenon governments are failing to act and business driven initiatives have a stronger likelihood of being successful. The most effective and feasible plans are the most likely to attract potential investors. This thesis will aim to assess solutions by quantifying their feasibility from a clean-up rate and business case potential. A fundamental element of any viable plan must rely upon the reintroduction of marine plastic pollution into a circular economy (see scope of work for further explanation). The goal of this thesis is to provide a solution space, balancing the willingness-to-pay from investors, the effectiveness and any other relevant factors that will be identified along the way.

THESIS OBJECTIVE

PLASTIC REACHING THE OCEANS – TURNING THE PROBLEM INTO VALUE
A methodology quantifying the feasibility and effectiveness of plastic recovery solutions from oceans, rivers and waterways

SCOPE OF WORK

As mentioned in the introduction, a viable plan must rely upon the reintroduction of marine plastic pollution into a circular economy (Figure 1). However, in reality this economy is linear where the plastics are wasted after a single use. The transition from a linear to a circular economy creates a highly complex challenge, a "wicked problem", but it also creates room for opportunities. This thesis will focus on one of those chains of the circular economy. Collecting the plastics is one of the important challenges to solve towards closing the loop, because it has the potential of adding (a monetary) value to the transition to a circular economy. Within the chain of collecting plastics, the scope will cover an assessment of solutions that recover plastics by collecting and removing from oceans, rivers and waterways. This assessment will be based on a to be developed methodology quantifying the feasibility and effectiveness of solutions. Solving this particular challenge will create more guidance during the design of future solutions by knowing how to effectively turn the problem into value.

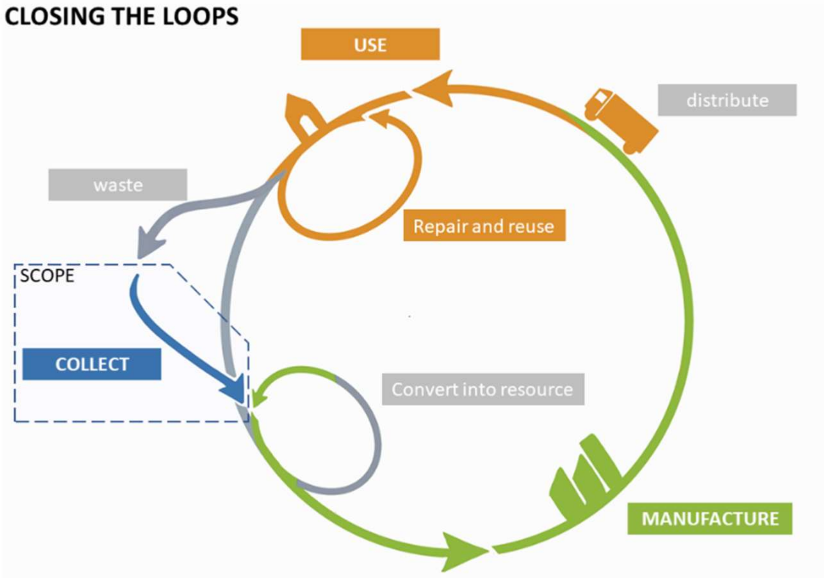


Figure 8.6 Circular economy for plastics

The rest of the loop is excluded from this thesis. It is important to mention that the other chains (such as the need for a proper breakdown of plastics to a base material - see green arrows in the figure; or the need for better repair and reuse of products - see orange arrows) have a similar and essential role in closing the loop, but will not be the focus during this thesis.

ORGANIZATION

The thesis objective is built up in three phases:

Phase 1: Describing and defining the problem of plastic reaching the oceans

Definition of the actual plastic waste problem, identifying its core, its hazards, causes and consequences, but also identifying the status quo. This phase is based on literature research, combined with qualitative interviews with people from the industry. The outcome of this research should identify the main parameters contributing to the feasibility and effectiveness of plastic recovery from marine and coastal environments.

Actions related to phase 1 are literature research covering the latest and most up-to-date scientific knowledge, with an expected duration of 4 weeks (full time). In parallel with the literature, interviews with parties heavily involved in the industry need to be held to identify current research topics and current approaches, with an expected duration of 4 weeks (full time). Examples of involved parties are the International Maritime Organization, the Chief Sustainability Officer of DNV GL, but also people responsible for actual projects (The Ocean Cleanup, REV, Tavaha). All of those actions will be mainly executed from Delft, Netherlands, but the interviews might require travelling. In total, this phase has an expected duration of 8 weeks.

Phase 2: Development of a methodology for assessing plastic recovery potential

During this phase, the found parameters from phase 1 are used to develop a methodology to systematically assess benefits and effectiveness of solutions. The goal of developing this methodology is to provide a decision support basis for those who want to assess whether a defined solution will work or not, how effective and resource demanding a given solution will be, and which conditions should be in place to ensure the solution will work as intended.

Actions related to phase 2 are a formulation of the requirements for this methodology (2 weeks), formulating a development plan (3 weeks) and the development of the methodology itself (10 weeks). All of these actions are preferred to be executed at DNV GL Headquarters (Høvik, Norway) for the majority of time.

Phase 3: Recommending feasible solutions with high impact and value by exploring the solution space
Here the found methodology of phase 2 is used to quantify the feasibility and effectiveness of solutions. The outcome of this phase should eventually create more guidance during design of future solutions by knowing how to effectively turn the problem into value.

Actions related to phase 3 are finding and selecting solutions to use for assessment (2 weeks), the assessment itself (4 weeks) and drawing conclusions and recommendations for future use (4 weeks). All of these actions are preferred to be executed at DNV GL Headquarters (Høvik, Norway) for the majority of time.

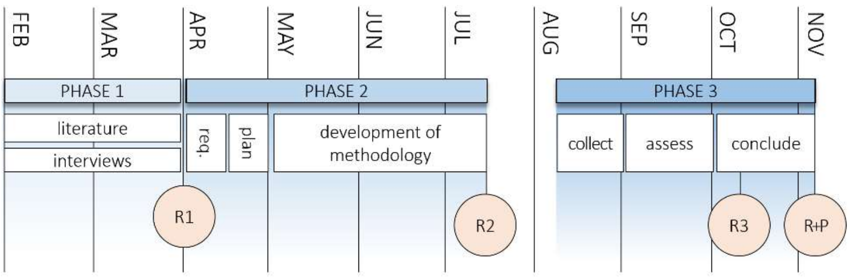
This project will be under the supervision of Arnstein Eknes, M.Sc. from DNV GL. Responsible for the supervision from Delft University of Technology is Prof.Dr. Eddy van de Voorde, together with Ir. Koos Frouws.

Writing and reporting will be a continuous process during all phases of the project. The supervisors will be provided with the latest information which will be discussed during progress meetings. Besides this, a few deliverables will be agreed upon in order to keep the separation between phases, this is further described in the time schedule below.

TIME SCHEDULE & DELIVERABLES

The proposed starting date of the thesis is 6/2/2018 stretching a period of roughly 36 weeks, which equals a study load of 45 ECTs. Estimated deadlines of deliverables are:

06/02/2018	Graduation workplan
31/03/2018	Report Phase 1
15/07/2018	Report Phase 2
16/07/2018-07/08/2018	summer holiday
15/10/2018	Report Phase 3
26/10/2018	Final report
01/11/2018	Final presentation



SECRECY

No secrecy for this thesis is necessary. However, the situation can occur that details of existing solutions are preferred to remain secret.

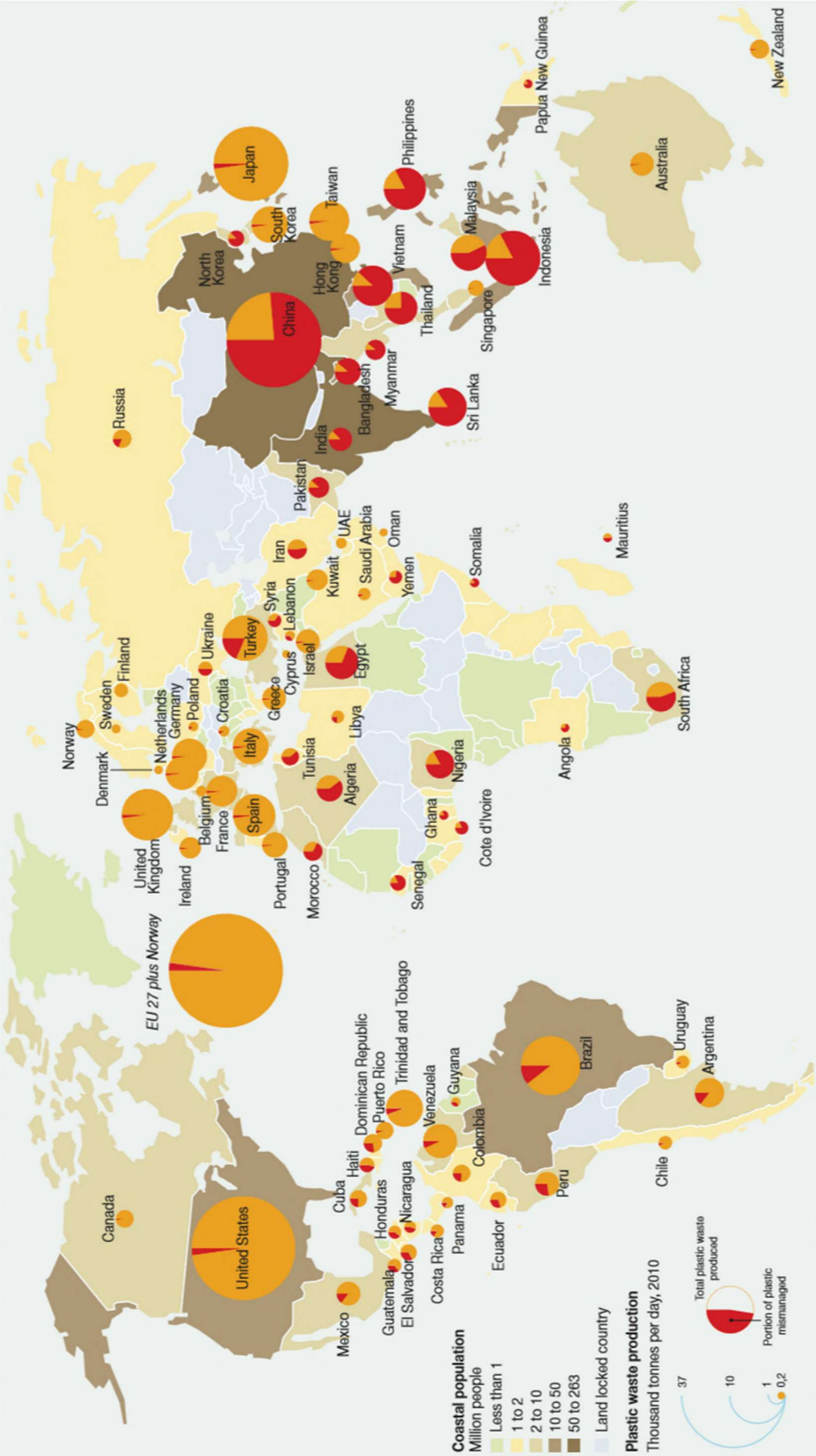
References

DNV GL AS, 2016. *Global Opportunity Report.*

International Maritime Organization, 2017. *IMO.* [Online]
Available at: http://www.imo.org/en/MediaCentre/HotTopics/marinelitter/Pages/default.aspx
[Accessed 4 February 2018].

Jenna R. Jambeck, e. a., 2015. Plastic waste impouts from land into ocean. *Science*, 13 February, Volume 347, pp. 768-771.

APPENDIX 2: Global map for waste management. Courtesy of (UNEP, 2016), information based on (Jambeck et al., 2015)



APPENDIX 3: The Japanese Government

The underlaying sources were officially published by the Japanese government and were carefully translated from Japanese to English for this project.

According to a recent publication of the Japanese government, the outline of plastic pollution in Japanese waters can be identified ('Japanese Government on Marine Litter', 2018):

- Coastal pollution (lost fishing gear along the coastline)
- Landfill
- Drifting garbage from other countries
- Severe damage of the degradation of marine environment including its ecosystem, degradation of coastal living environment, but also increasing difficulty in ship navigation and manoeuvring, and a strong adverse effect on tourism and the fishing industry.

The Japanese government identifies the drifting garbage as the most problematic part, since the origin lays in other countries. According to the World Economic Forum, Japan is listed at the 30th place in plastic pollution with 60.000 t / year. As sources as Plastic Adrift shows, the origin of waste ending up in Japanese waters is originating from China (3.530.000 t/year), Indonesia (1.290.000 t/year), Philippines (750.000 t/year), Vietnam (730.000 t/year), Sri Lanka (640.000 t/year), (World Economic Forum, 2016). The Japanese government is aware of the consequences of plastic pollution and use similar scientific sources as Western governments to support that. Notable is that Japan immediately connects the causes and consequences of the problem, with the urge for strong countermeasures to prevent and recover the outflow. Where other cultures ask for more research, Japan actively promotes direct solutions. An explanation for this are the unique laws the country enforces. One of those is Article 29 of the Coastal Landfill Disposal Promotion Act, an act that is written to 'preserve and protect the beautiful and rich nature'. This act has been put into action before, referring to the Fukushima Daiichi nuclear disaster and many other environmental disasters the country had to face in the past. The government has set the goal to 'preserve the good landscape and the environment on the coast, by smooth treatment and suppression of plastic pollution occurrence'. The basic principle contains the following steps:

- Conservation and rehabilitation of comprehensive coastal environment – conservation of good landscape, consideration for securing biodiversity
- Clarification of responsibility and promotion of smooth processing – Clarification of responsibilities of stakeholders including coast managers.
- Effective suppression of the occurrence of shore-borne objects and the like – common challenges leading from mountains to rivers and the sea
- Conservation of marine environment – indispensable for a rich and moist and civic life
- Secure appropriate role sharing and cooperation among diverse entities – promotion of active efforts by citizens
- Promotion of international cooperation – common challenges for our country and neighbour countries.

Supported by the following financial measures:

- The government must take necessary fiscal measures to promote coastal drift countermeasures.
- Government islands and other areas where large amounts of coastal drifts drift from overseas or other local public entities, should be given special consideration to the expenses required for local shipping organizations to deal with coastal landings.
- The government will endeavour to give fiscal consideration to promote the activities of private organizations and others.

The nation acknowledges that assistance with subsidies and promotion of countermeasures against marine waste is necessary to control it. It will not lead to problem solving, since the source is not changed, but the public corporations are responsible for the treatment of drifting waste. For now, these

countermeasures are a way to act now and control the situation, so the nature can recover. As will be discussed later, the Japanese are also working on future development of addressing the source of the problem directly.
They have taken the following steps so far:

- The government has enforced regional measures supporting local projects.
- The business scheme they propose is based on Article 29 of the Coastal Landfill Disposal Promotion Act (part of Heisei 21), where prefectures (administrative division of Japan), municipalities, etc. will make a regional plan on marine waste, collection and treatment, and measures to control development. The subsidization rate is in accordance with the situation, carried out in which location (remote islands), depopulations, peninsular areas, etc. The subsidy rate is based on which of the outlined factors is addressed in the business plan and what the quality of their work was (performance based). In the past they budget record was 400 million yen in 2008 and 2.7 billion yen in 2010.

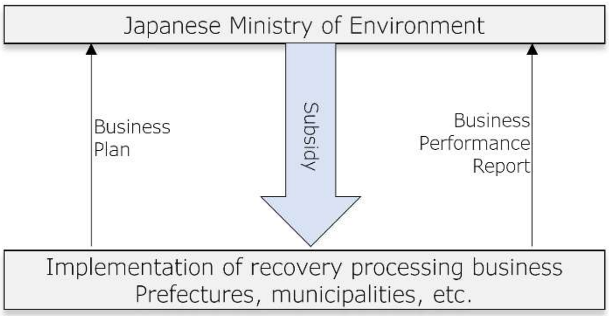


Figure 8.7 Overview of Japanese business scheme

Although the Japanese seem quite far ahead of the Western world with their concise approach, the expected outcome is not quantified at all. They describe the outcome as a 'promotion of marine waste management worldwide, preserving the marine environment, where the excellent landscape of the oceans should be maintained and preserved'. Added to that, 'the beautiful and prosperous as indispensable for the promotion of regional social and regional core industries such as fisheries and tourism'. Interestingly enough, cultural values and benefits seem to function as a motivation itself, whereas the Western approach mentions its worst outcome to activate society.

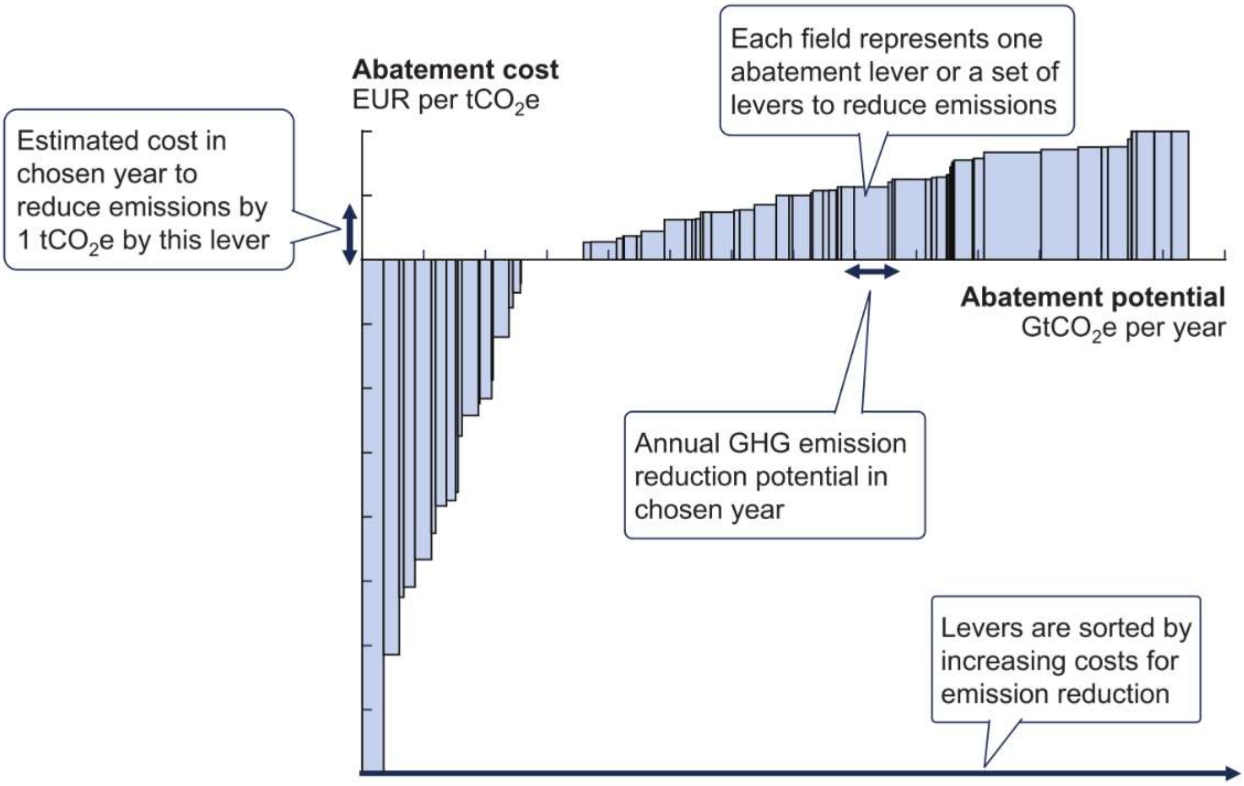
Apart from financing, the government takes the full responsibility for surveys along the entire coastline to monitor plastic waste changes. This is executed by sight surveys, collection of microplastics and collection of ocean floor waste. In particular determining the distribution status in areas around Japan, PCB absorbed in microplastics and other amounts of harmful chemicals. These surveys have been going on for 5 years now, where the largest number of garbage was in Shimonoseki City, where 47000 pieces of garbage were drifting. 80-90% of the garbage showed to be plastic waste. It is estimated that the Kamisu city area in Ibaraki Prefecture is half of the total amount of garbage, this is an effect of the Great East Japan Earthquake and typhoon. With this research the Japanese have found that the amount of plastic waste is the largest in the waters around Japan (East Asia), they have estimated that the problem is over 17 times larger than in the North Pacific Gyre (Isobe *et al.*, 2015).

How Japan looks at the international perspective, it that they will take an active role in fostering international momentum, through international partnership, and promoting efficient and effective measures, where best measures are shared (UNEP, APEC, G20, FAO, IMO).

Besides this global collaboration, Japan is also part of regional collaborations between Japan, China, Korea and Russia, by organizations such as TEMM (Three Countries Environment Ministers Meeting, including China-Korea and Japan), and NOWPAP, the Northwest Pacific Region Maritime Action Plan. For as far as the information is accessible, these regional initiatives seem to have more concrete efforts, such as regular workshops and official meetings, exchange of information on policies and research results, aimed to develop into policy dialogue in the near future, but also to strengthen cooperation between countries to support harmony of monitoring methods and implementation of joint surveys and recovery. Altogether, Japan serves a good example with their active role in plastic recovery, where the foundation goes back to cultural values as taking care of nature, and the ability to connect that to a clear role division and proper financing.

APPENDIX 4: Cost-benefit method: Marginal Abatement Cost Curve

Similar methodologies for quantifying feasibility and effectiveness have been made when a new market was arising the cost-benefit should be assessed. Meaning that, even though this thesis is addressing a new market opportunity, similar steps have been taken before that can be useful for this research. An inspiring example are the Marginal Abatement Cost Curves (MACC) developed for the reduction of greenhouse gasses (GHG) by McKinsey&Company and DNV GL (McKinsey&Company, 2009). The figure below shows an example of a MAC curve, that depicts the available technical measures, their relative impact (emission volume reduction potential) and cost in a specific year. Each bar should be examined independently to quantify both dimensions.



APPENDIX 5: Casualty report Ojibway

CASUALTY DETAIL

IMO/LR/IHS No.	5105831	Incident No.	9839592
Incident Date	2013-11-10	Name at Time of Incident	OJIBWAY
Casualty Type	Hull/Mchy. Damage	Incident Type	Casualty

SHIP DETAILS AT TIME OF INCIDENT

Ship Name	OJIBWAY	Flag	Canada
Ship Type	Bulk Carrier, Great Laker	Year of Build	1952
GT	12296	DWT	18602
Classification		Ship Status	In Service/Commission
Owner	Lower Lakes Towing Ltd		

INCIDENT & CARGO

SUSTAINED LEAK IN STERN TUBE WHILST BERTHED AT SOREL, QC, CANADA ON 10/11/13. SUBSEQUENTLY REPAIRED AND RETURNED TO SERVICE.

PROCEEDED TO HAMILTON, ON, CANADA ARRIVING 12/11/13 FOR INSPECTION. THE LEAK WAS CAUSED BY A LENGTH OF FISHING LINE WHICH HAD BECOME ENTANGLED IN THE PROPELLER AND DAMAGED THE STERN TUBE OUTER SEAL. OBSTRUCTION REMOVED AND REPAIRS EFFECTED AT HAMILTON.

Incident Type	Casualty	Casualty Type	Hull/Mchy. Damage	Incident
Lives Lost	No	Missing	No	
Detail Status	MOORED/ANCHORED	Cargo Status	Unknown	Cargo
Dangerous Cargo	Unknown	Pollution Occurred	No	Pollution

VOYAGE DETAILS

Voyage From	Sorel, Qc	Voyage To	
Removal from Scene	Proceeded For Repair	Assistance Given	Unknown

EVENT DETAILS

Sequence	01	Date	2013-11-10
Initial Event	Hull/Mchy/Equip.Damage/Failure	Event Action	Fouled By
Event Component	Propeller	Position	Lower Aft Outer/Outbo
External	Wire, Ropes	Weather	Unknown/No Reported

7/10/2018 Casualty Detail - Sea-web

Sequence	02	Date	2013-11-10
Initial Event	Hull/Mchy/Equip.Damage/Failure	Event Action	Damage(D)
Event Component	Stern Tube	Position	Lower Aft Outer/Outbo
External	Wire, Ropes	Weather	Unknown/No Reported

OTHER SHIPS INVOLVED

CASUALTY LOCATION

Marsden Grid Ref	152	Location Type	In Port/Harbour/Dock/At...	Port	Sorel, QC
Zone	Great Lakes	Position	46 03 00 N 073 07 00 W		Click here to see casualty displayed in Bing Maps

DISPOSAL

Not a Disposal, See Other Sections

APPENDIX 6: Casualty report Guldrangur

CASUALTY DETAIL

IMO/LR/IHS No.	8315944	Incident No.	0013075
Incident Date	2018-06-08	Name at Time of Incident	GULDRANGUR
Casualty Type	Hull/Mchy. Damage	Incident Type	Casualty

SHIP DETAILS AT TIME OF INCIDENT

Ship Name	GULDRANGUR	Flag	Russia
Ship Type	Fishing	Year of Build	1984
GT	1040	DWT	558
Classification	Russian Maritime Register (IACS)	Ship Status	In Service/Commission
Owner	Saami Co Ltd		

INCIDENT & CARGO

PROPELLER FOULED BY FISHING NET, DISABLED AND DRIFTED WHILST FISHING IN THE NORWEGIAN SEA 34 MILES SW OF BEAR ISLAND, NORWAY IN LAT. 73 56' 43"N, LONG. 017 57' 37"E ON 08/06/18 IN HEAVY WEATHER.

INITIAL ATTEMPTS BY CREW TO REMOVE THE OBSTRUCTIONS UNSUCCESSFUL. FVS 'ARKHANGELSK' AND 'MELKART 2' ATTENDED THE SCENE. SUBSEQUENTLY TAKEN IN TOW BY TUG 'KAPITAN BEKLEMISHEV' ON 11/06/18 TO KIRKENES, NORWAY ARRIVING 15/06/18 FOR INSPECTION AND REMOVAL OF OBSTRUCTIONS.

Incident Type	Casualty	Casualty Type	Hull/Mchy. Damage	Incident
Lives Lost	No	Missing	No	
Detail Status	FISHING/TRAWLING	Cargo Status	Unknown	Cargo
Dangerous Cargo	No	Pollution Occurred	No	Pollution

VOYAGE DETAILS

Voyage From	Tromso	Voyage To
Removal from Scene	Towed/Transported Away	Assistance Given

EVENT DETAILS

Sequence	01	Date	2018-06-08
Initial Event	Hull/Mchy/Equip.Damage/Failure	Event Action	Fouled By
Event Component	Propeller	Position	Lower Aft Outer/Outbo
External	Wire, Ropes	Weather	Heavy Weath

OTHER SHIPS INVOLVED

CASUALTY LOCATION

Marsden Grid Ref	287	Location Type	At Sea	Port
Zone	Russia, Arctic & Bering Sea	Position	73 56 43 N 17 57 37 E	Click here to see casualty displayed in Bing Maps

DISPOSAL

Not a Disposal, See Other Sections

APPENDIX 7: Vessel density maps for appendix 5 and 6 respectively (source: www.marinetraffic.com)