HOW THE OCEANS CAN CLEAN THEMSELVES

A FEASIBILITY STUDY

BOYAN SLAT

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EXECUTIVE SUMMARY

BOYAN SLAT • HESTER JANSEN • JAN DE SONNEVILLE

Every year we produce about 300 million tons of plastic, a portion of which enters and accumulates in the oceans. Due to large offshore current systems called gyres, plastic concentrates in certain offshore areas, of which the Great Pacific Garbage Patch between Hawaii and California is the best-known example.

The damage to sea life is staggering: at least one million seabirds, and hundreds of thousands of marine mammals die each year due to the pollution. Even worse, the survival of many species, like the Hawaiian Monk Seal and Loggerhead Turtle, is directly jeopardized by plastic debris.

Figure 1 Albatross with plastic in its stomach. Photo by Chris Jordan

Marine species often become entangled in larger debris, leading to “injury, illness, suffocation, starvation, and even death” (NOAA, 2014). Smaller fragments can be mistaken for food and eaten, causing malnutrition, intestinal blockage and death (Figure 1). When marine animals eat plastic, harmful chemicals move up the food chain. Ingestion of and entanglement in marine debris by marine animals has increased by 40% in the last decade. Furthermore, plastics can transport invasive species and toxic substances over great distances.

The problem does not end there. Marine debris causes an estimated $1.27 billion in fishing and vessel damage annually in the region of the Asia-Pacific Economic Cooperation (APEC) alone. Moreover, the removal of garbage from coastlines costs up to $25,000 per ton of plastic.

Figure 2 Schematic overview of the five rotating currents, called gyres, where floating plastic accumulates

Figure 3 A preliminary design of a collection platform (Erwin Zwart – Fabrique Computer Graphics)

IN SEARCH OF A SOLUTION

Even if we manage to prevent any more plastic from entering the oceans, the natural loss of plastic from the gyres is slow and likely low; therefore, a cleanup is still necessary. Since the problem gained widespread attention at the beginning of this century, several cleanup concepts have been proposed, each based on vessels with nets – essentially, fishing for plastic. Unfortunately, even though the concentration of plastic in these five subtropical gyres is extremely high compared to the rest of the oceans, plastic is still spread over millions of square kilometers. Hence, it would likely take many billions of dollars and thousands of years to clean up such an area using those methods (Moore, 2011). By-catch and emissions would likely be problematic using this approach. Furthermore the ocean is not a particularly friendly place to work. Why move through the oceans, if the oceans can move through you?

ABSTRACT

The world's oceans are characterized by a system of large-scale rotating currents, called 'gyres'. The ocean systems are constantly moving as a result of the turning of the earth and wind patterns. The five major gyres are the Indian Ocean Gyre, the North Atlantic Gyre, the North Pacific Gyre, the South Atlantic Gyre and the South Pacific Gyre. If the ocean's water is constantly moving according to predictable patterns, so is the plastic pollution. This led to the idea of a 'passive cleanup': using an Array of floating barriers fixed to the sea bed to catch the debris as it flows past on the natural ocean currents.

THE CONCEPT

The Ocean Cleanup Array utilizes long floating barriers which —being at an angle— capture and concentrate the plastic, making mechanical extraction possible. One of the main advantages of this passive cleanup concept is that it is scalable. Using the natural circulation period of the North Pacific Subtropical Gyre, cleanup duration could be reduced to a minimum of just 5 years.

Using a passive collection approach, operational expenses can potentially be very low, making the cleanup more viable. Furthermore, converting the extracted plastic into either energy, oil or new materials could partly cover execution costs.

Because no nets would be used, a passive cleanup may well be harmless to the marine ecosystem and could potentially catch particles that are much smaller than what nets could capture.

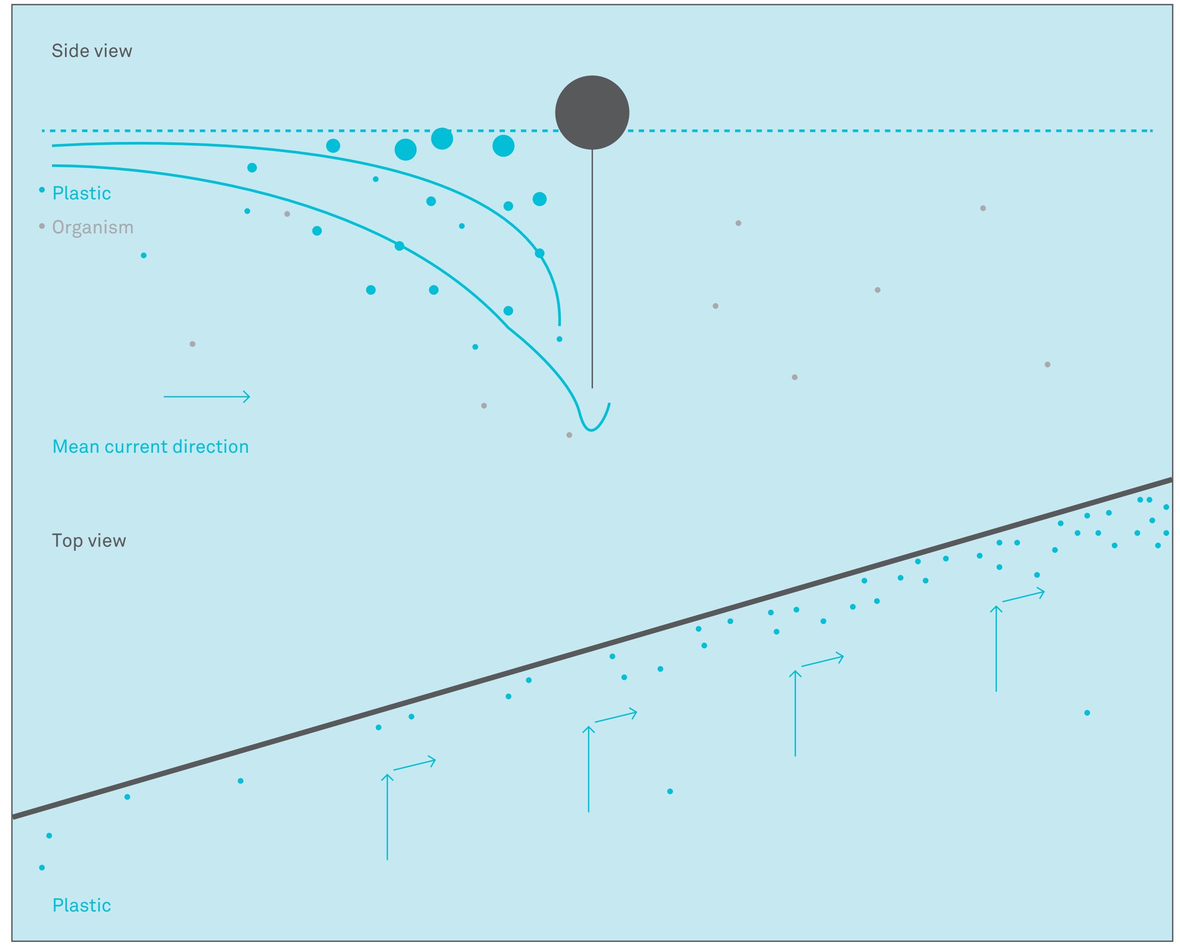


Figure 4 Simplified and schematic cross-section view of a floating barrier. The blue dots represent plastic particles, while the grey dots represent zooplanktonic organisms.

THE FEASIBILITY STUDY

Between April 2013 and May 2014, The Ocean Cleanup investigated the technical feasibility and financial viability of The Ocean Cleanup Array concept. With costs covered by a crowdfunding campaign, a global team of over 100 people, companies and institutes have collaborated to produce an in-depth study.

This feasibility study examines the physical properties of plastic pollution; technical feasibility in terms of fluid dynamics, structural engineering and operations; and describes the preliminary testing that has been performed. It assesses any possible negative environmental effects and legal consequences. Moreover, the study evaluates the quality of ocean plastics, as well as possible methods to process it —including a cost—benefit analysis. Finally, the feasibility study outlines recommendations for future work.

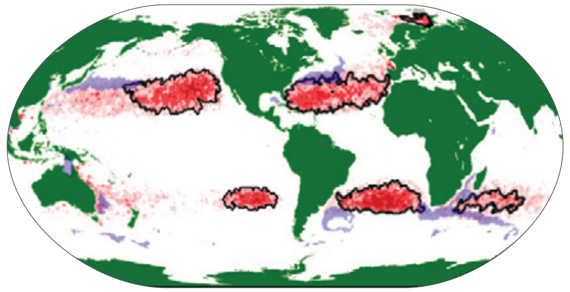


Figure 5 Initial simulation plastic distribution. The locations where plastic release begins are visualized in red and purple. source: Van Sebille, England, & Froyland, 2012.

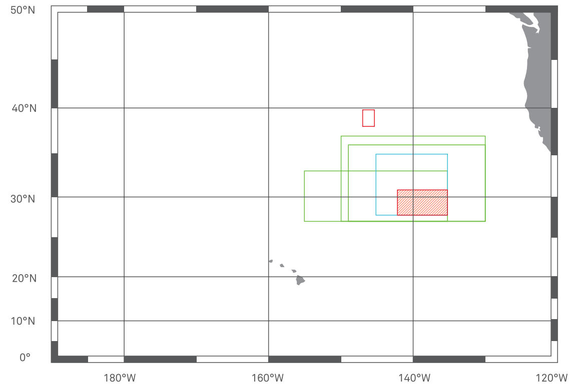


Figure 6 Map showing the areas in which the highest concentration of plastic debris has been predicted by Maximenko et al., 2012, van Sebille et al., 2012 and Lebreton et al., 2012, in green. The highest measured plastic concentration is displayed in blue, while the areas containing favorable seabed conditions are depicted in red.

PLASTIC POLLUTION HOTSPOTS IN OCEAN GYRES

Ocean surface current models were used to identify plastic pollution “hotspots” and subsequent measurement data identified the North Pacific Subtropical Gyre as the area where this project would have the most impact (Figures 5-6). The Ocean Cleanup conservatively estimates the quantity of floating plastic in the North Pacific accumulation zone at 140 thousand metric tons: 21 thousand tons smaller than 2 cm and 119 thousand tons larger than 2 cm. However, more research is needed to increase the accuracy and reliability of these figures. Sampling of ocean plastic is still limited—both spatially and temporally—particularly for large (centimeter/meter-sized) plastic items.

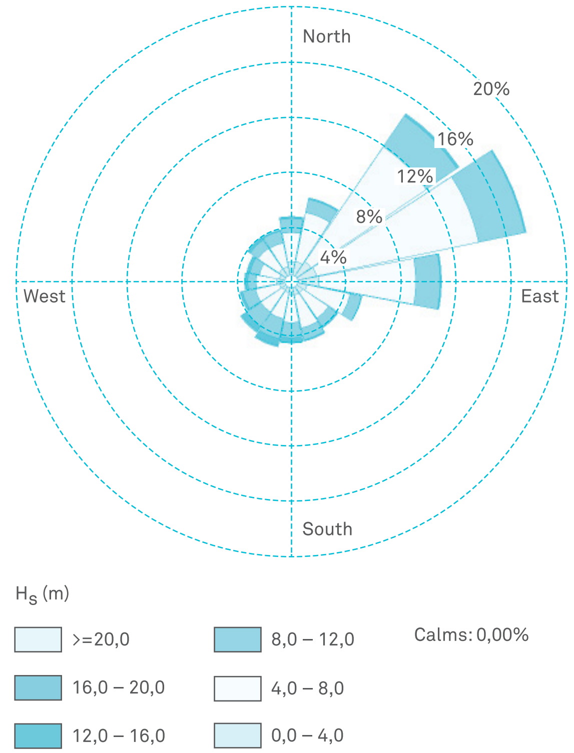
DETERMINATION OF LOCATION

On the basis of ocean current models, ocean depth and measured plastic concentrations, The Ocean Cleanup has chosen 30°N, 138°W as the preliminary coordinates for placement of The Array.

ENVIRONMENTAL CONDITIONS IN THE NORTH PACIFIC GYRE

Using data from weather buoys and satellite recordings, current, wave and wind conditions were estimated for the area of interest (Figures 7-9).

The following values have been used as input parameters for structural engineering and fluid dynamic chapters of the report: waves predominantly derive from the northwest (NW), and to a lesser extent also from the northeast (NE) sector. Waves from the northwest (NW) sector are swells generated in the North Pacific Ocean, and waves from the northeast (NE) sector are sea waves. Over 95% of waves are lower than 4.5 – 5.5 m. The maximum significant wave height (H_s) is 12.2 m with a 100-year return period. The wind predominantly comes from the northeast to east (NE-E) sectors. A mean current velocity of 14 cm/s has been calculated for the area.



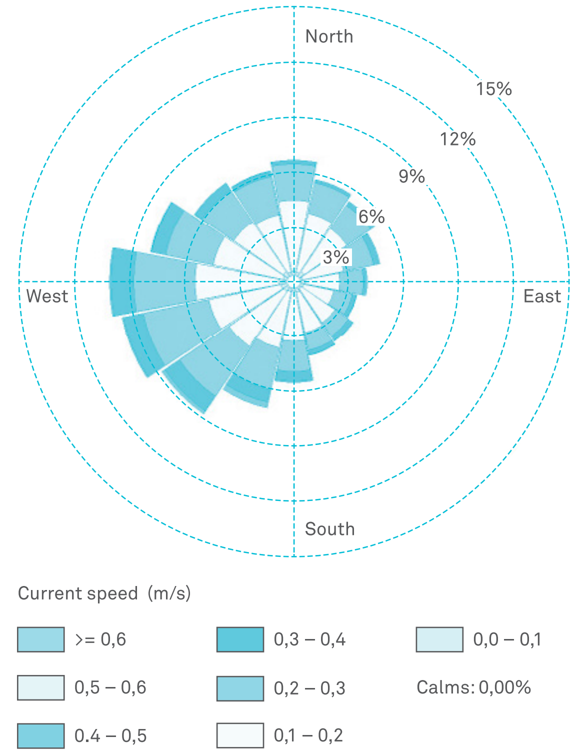


Figure 7 Wind from direction rose for NOGAPS reanalysis data

Figure 8 Surface layer current rose

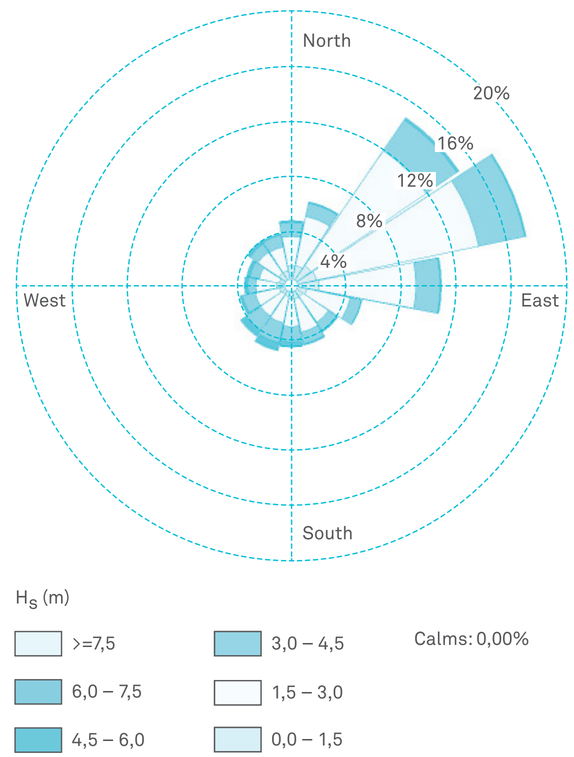


Figure 9 Significant wave height – wave from direction rose

Figure 10 The multi-level trawl, used for sampling plastic concentrations

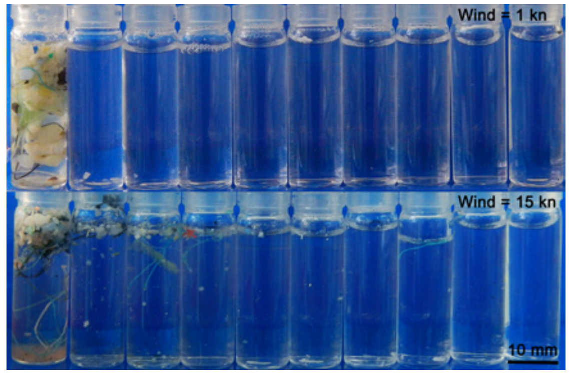


Fig 11 Glass jars with filtered water and plastic samples collected under different wind conditions (1 and 15 knots) From left to right: samples from 0 - 0.5m, 0.5 - 1m, 1 - 1.5m, 1.5 - 2m, 2 - 2.5m, 2.5 - 3m, 3 - 3.5m, 3.5 - 4m, 4 - 4.5m, and 4.5 - 5m depth. Source: Reisser & Slat 2014, submitted

VERTICAL DISTRIBUTION OF PLASTICS

The concentration of plastic pollution at various depths is an important consideration. This vertical distribution of plastic debris was measured in the North Atlantic Subtropical Gyre using a specially designed net system capable of sampling down to a given depth. Therefore, a floating barrier depth of 2-3 m is likely to capture most of the total plastic mass floating at the Great Pacific Garbage Patch. The data also suggests there is a relationship between wind speed and vertical distribution of plastic mass, similar to what was observed by Kukulka, et.al. (2012) for number of plastic particles and wind speed.

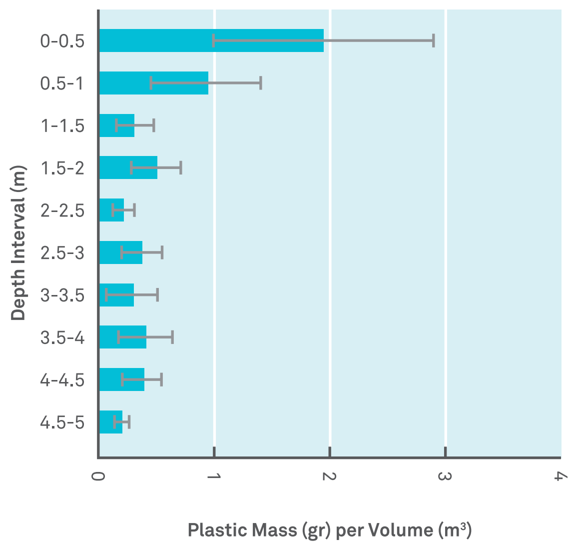


Figure 12 Mean and standard error of plastic concentration (mass per volume) at different depth intervals (N = 12 trawls).

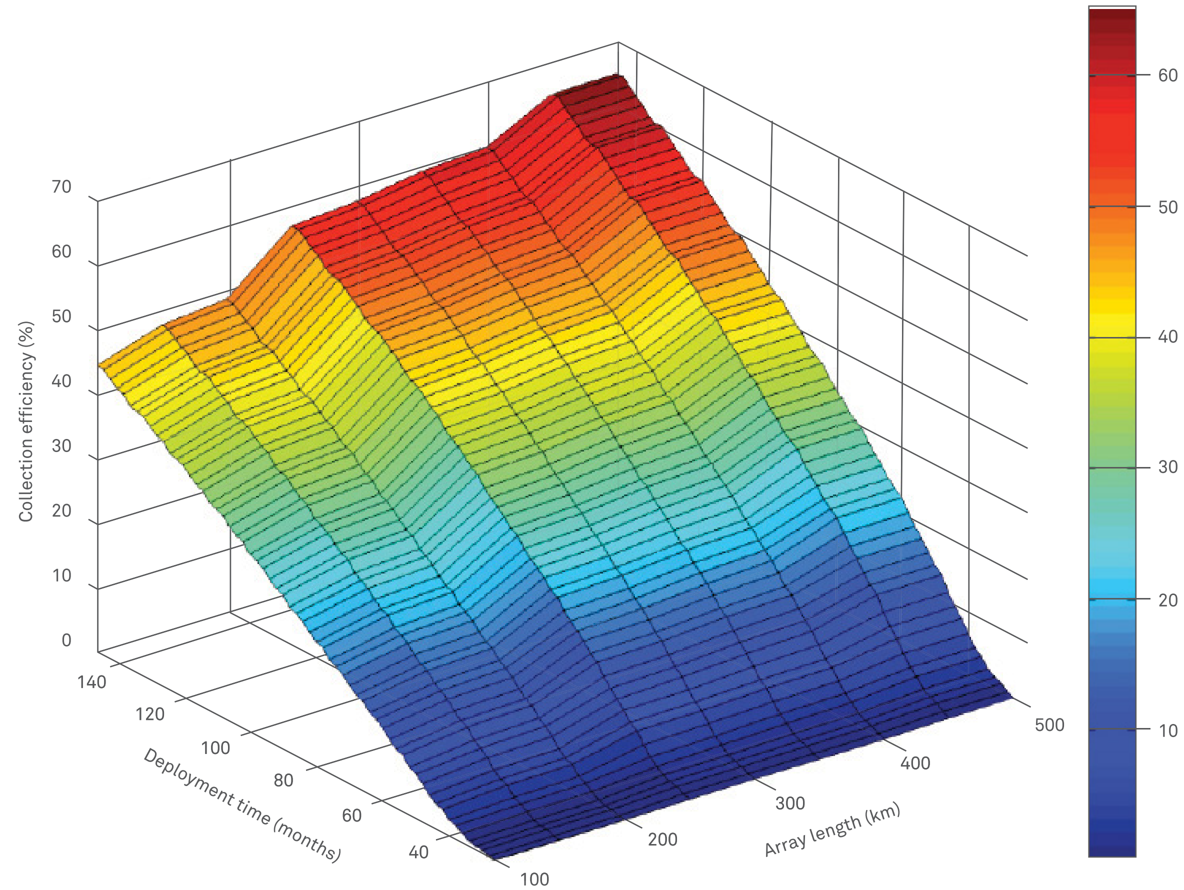


Figure 13 A graphic representation of the dependency between the field efficiency, total Array length and deployment time. To increase field efficiency, either the total Array length or deployment time has to increase.

CLEANUP TIME AND REQUIRED ARRAY LENGTH

The Ocean Cleanup investigated the relation between Array length, deployment time and field efficiency. It follows that to increase field efficiency, either the total Array length or deployment time has to increase. A deployment time of 10 years and an Array length of 100 km was chosen, resulting in a field efficiency of 40-45%.

INVESTIGATING BASIC PRINCIPLES

Computational Fluid Dynamics (CFD) has been used to study the catch efficiency, the transport of plastic along the boom, and the forces acting on the boom (Figure 13).

Variables such as particle size, density and release depth were taken into account in determining which particles would be caught by or escape underneath the boom. Combining this data with modeled mass distribution and vertical distribution, a capture efficiency of 79% of mass was calculated. No micro plastics (particles smaller than 2 cm) were captured under the modeled conditions. However, all medium and large size plastics (irrespective of the depth within the top 3 m) are caught. The capturing of large debris prevents the creation of small debris by photo-degradation.

The velocity of the plastic along the barrier depends on the boom angle, but is about 40% of the initial velocity when placed at an angle of 30°.

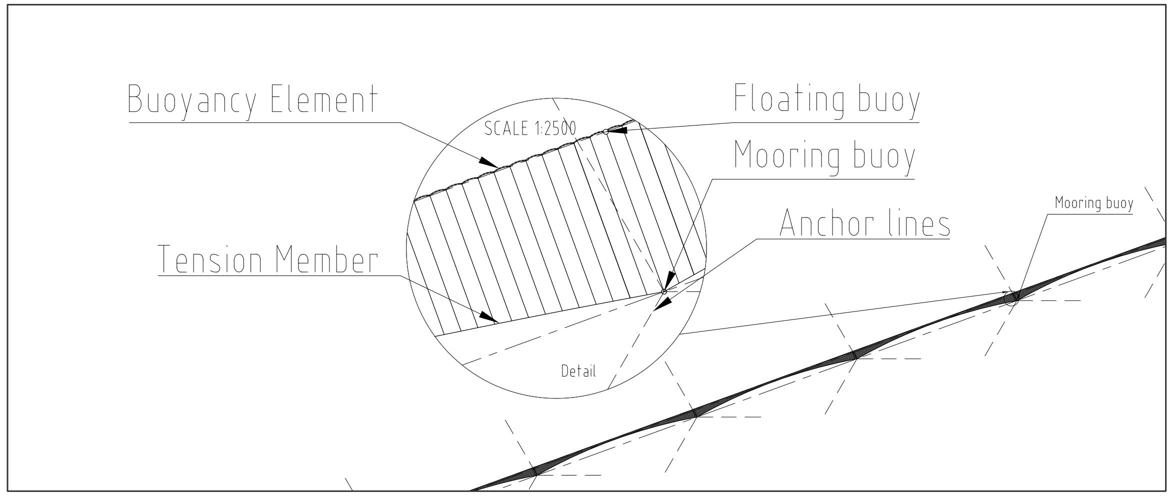


Figure 14 Tension cable impression

LOADS ON THE BOOM

A boom-and-mooring model was set up in Orcaflex to determine the mid-effective tension (the load on the boom) as function of boom length. Forces were determined for a generic boom with a draft of 3 m, at a significant wave height of 5.5 m, which was set as the maximum operational significant wave height.

For boom lengths used in the simulation, the relationship between force and boom length was found to be essentially linear. The tension is higher for the Dyneema-tensioned boom than for the neoprene and steel boom. This is due to its high stiffness compared to other options. The steel boom has neoprene links that lower the stiffness significantly. Although the boom likely would not be entirely manufactured out of Dyneema, its readings were used during the dimensioning of the materials as a conservative estimate.

OVERTOPPING

Orcaflex also found that if the boom were too long, high tension would prevent the boom from following the waves, resulting in overtopping. This is an undesired effect, because plastic would likely be lost in the process, impacting capture efficiency.

As illustrated in Figure 15, the boom can follow the shape of the wave, but in the second image the tension force spans the boom in such a way that it remains straight and waves overtop it. If overtopping is to be avoided, it was found that the maximum length of an individual boom should be 1.4 km.

TENSION CABLE CONCEPT DESIGN

The Ocean Cleanup developed a boom design in which the boom and tension cable are separated. This design allows the boom to move with the waves, rather than being restricted by the load-carrying part of the boom—regardless of the stiffness of the tension cable. The boom is connected to the tension cable every 60 m, transferring its load to the cable. Furthermore this design allows the boom to move along with the rotational motion of the waves, reducing the forces on the tension cable. The use of a tension cable is also included in a patent application from The Ocean Cleanup.

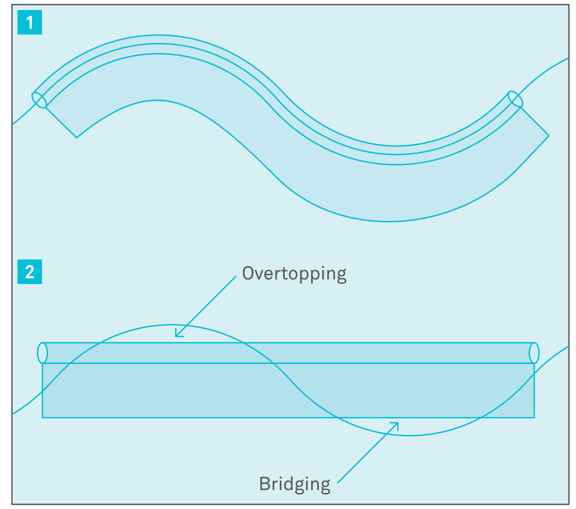


Figure 15 Effect of a too high-tension force along the boom: in the top image, the boom can follow the shape of the wave, but in the bottom image, the tension force spans the boom in such a way that it remains straight

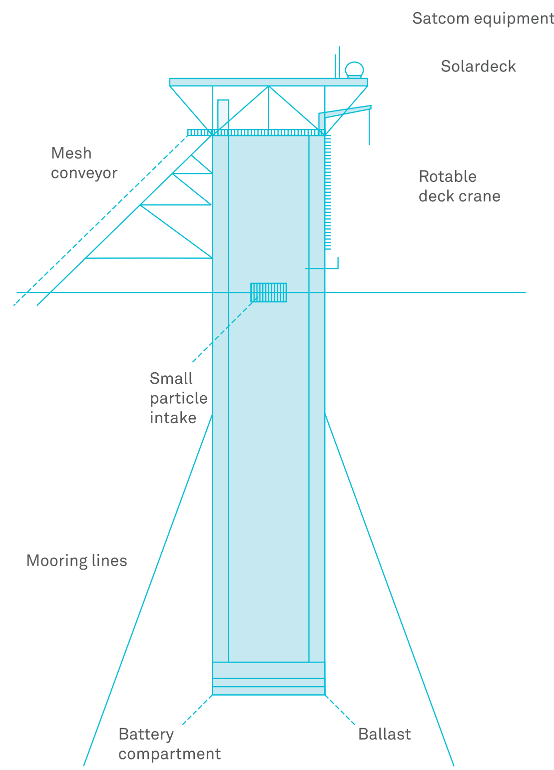


Figure 16 Preliminary design of a classic spar as a processing platform.

MOORING

The mooring systems required for station-keeping the structure are novel due to the unprecedented depths at which they would be placed. Given an average depth of about 4 km, a fiber rope mooring system is the only option available. To ensure durability of the system, chain and wire rope is used at the bottom and top ends. A Stevmanta Vertical Load Anchor (surface area 14 m²) is sufficient to withstand the design loads including the safety factor. A three-line system was chosen for all mooring points.

Vryhof Anchors confirmed that with current knowledge, mooring at the given water depths is feasible and installation of all system components can be done from the water surface. The mooring configuration is similar to proven solutions at 2,500 m of water depth.

THE PROCESSING PLATFORM

The platform design is based on a spar, being a stable, cost-effective and proven hull-type. This design consists of a buffer for the collected plastic in the hull of the spar, with a processing-equipment deck as a topside (Figure 16). The hull has a cylindrical shape with a diameter of 11m and a height of 58m. For the storage of plastic, a volume of 3,000 m³ is reserved in the hull. Although for transport a volume of 6,000 m³ has been reserved, this includes the added water necessary to pump it from platform to ship. The plastic collection rate will total 65 m³/day, which means the plastic collected has to be picked up by a ship every 45 days.

The main deck features processing equipment, including the top of the mesh conveyor, a shredder for large debris and electrical systems. Additionally, the deck incorporates a workshop and a 50-ton crane to lift spare machinery. Photovoltaic panels mounted on the roof over the main deck will provide the primary power supply. The platform is equipped with a slurry pump to extract small particles, coupled to a centrifugal separator for dewatering purposes.

Taking into account a cost of €5 per kg of steel (including construction), and a total weight 2,800 tons of steel, the costs of the platform are an estimated €14 million (excluding equipment and mooring). For transshipment and transport of the collected debris a second slurry pump will be used. The costs to transport the garbage to land have been calculated to be €1 million euro per year, or €0.14 per kg plastic.

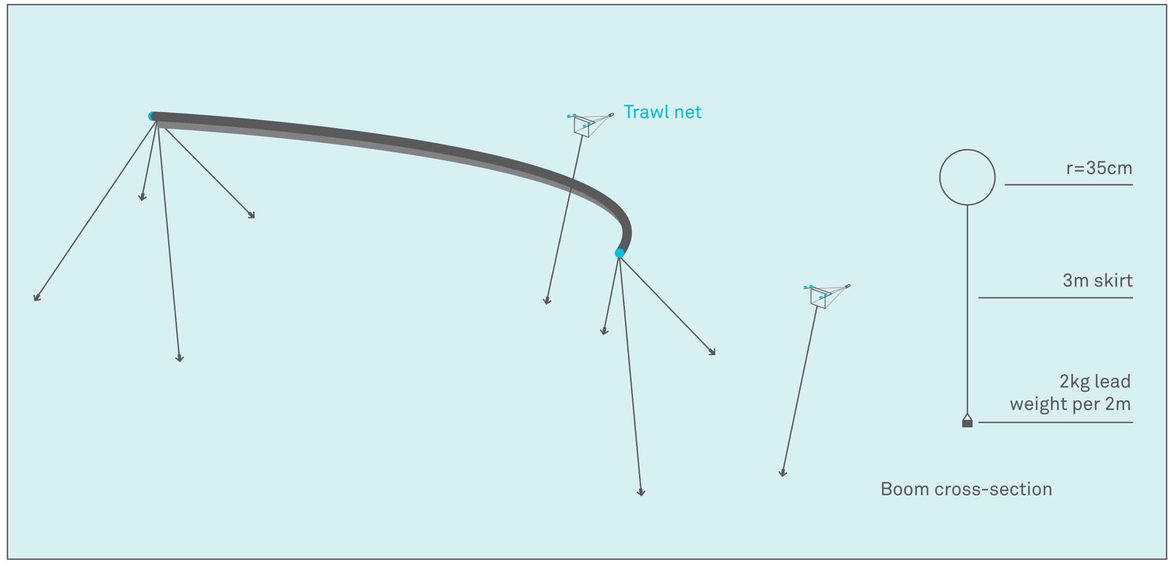


Figure 17 Mooring configuration. Schematic drawing of the planned mooring configuration of the booms and trawls.

ENVIRONMENTAL IMPACT

Because they are effectively neutrally buoyant, both phytoplankton and zooplankton are likely to pass underneath the barriers. But even assuming the worst—The Ocean Cleanup Array would harvest all the plankton it encounters—this would constitute a maximum loss of 10 million kg of planktonic biomass annually. Given the immense primary production of the world oceans, it would take less than 7 seconds to reproduce this amount of biomass.

With regard to vertebrates, harm caused by the barriers seems unlikely because non-permeable barriers are used, although some bycatch may occur in the near vicinity of the platform's extraction equipment. To prevent the possible impact on vertebrates, active deterrent techniques could be implemented near the extraction equipment.

The carbon footprint analysis showed the greenhouse gas emissions of the entire Ocean Cleanup project are 1.4-5 million kg of CO^2, depending on the chosen scenario. To put this into perspective, it is equal to the production of only 370-1,400 cars based on an average consumption of driving 20,000 km per year. The calculation of the carbon footprint revealed that the life-cycle stage 'Marine Transport' has the largest environmental impact. This impact can be reduced by limiting the on-site time of the vessel, as well as by using a highly energy-efficient vessel. The transportation of more plastic per vessel and per cycle could lead to a longer cycle time and a smaller carbon footprint. The use of solar energy reduces the platform's carbon footprint.

Figure 18 Copepoda individuals are highlighted in the red circle as observed under the microscope.

Figure 19 The Ocean Cleanup volunteers collecting beached plastic for analyses of plastic waste processing options. Photo by Megan Lamson / HWF

PROOF OF CONCEPT

A first proof-of-concept test performed at the Azores Islands validated the capture and concentration potential of a floating barrier with a skirt depth of 3 m, in moderate environmental conditions. In addition, qualitative data suggested that the barrier does not catch zooplankton as the net behind the boom appeared to have caught an equal amount of zooplankton as the net next to the boom (Figure 18).

PLASTIC MATERIAL ANALYSIS AND PROCESSING OPTIONS

Although the possibility of processing plastic into a useable and valuable material does not determine the feasibility of the Array, a valid question is: What would The Ocean Cleanup do with the collected plastic?

In order to investigate a representative sample of North Pacific Gyre debris, half a ton of plastic was collected on a remote beach on Hawaii Island. See Figure 19.

From the degradation tests, it can be concluded that the polyolefin samples were less degraded than expected. The degree of degradation of high-density polyethylene (HDPE) appears particularly mild both when compared to studies of accelerated aging under controlled conditions and when compared to the degradation found for polypropylene (PP) from the same sample origin.

Pyrolysis tests have showed that there is at least one method in which ocean plastic can be reused. According to the companies involved in the testing, the quality of the pyrolysis oil obtained from the polyolefin fraction of marine debris is comparable to that obtained as regular input in their pyrolysis plants. It appears that the production of marine fuel is more attractive due to its substantially higher yield of 77% for the target fraction when compared to the gasoline producing process with a final yield of 53% for the gasoline fraction.

LEGAL ISSUES

This study also provides a high-level overview of key legal issues that may impact The Ocean Cleanup.

First, concerning the question of who owns the plastic in the oceans, there are three different legal constructs in play. As most plastic is unlabeled and degraded before being caught, the owner of the plastic cannot be traced, and therefore salvage is not possible. Laws of abandonment cannot be used, as virtually all the traces, including owner information, are lost in the high seas. This leaves the law of the finds, that is based on the following principles: i) intent of the finding party to establish possession over the property in question; ii) actual possession as in exerting physical control over the property; and iii) a determination that the property has been abandoned by the owner. Based on this law, it is assumed that The Ocean Cleanup can take ownership of the plastic collected in the high seas.

Second, because The Array presents a unique situation that poses questions regarding shipping right-of-ways and hazards to shipping traffic, it may have to abide by additional safety regulations from either the flag-state or the International Maritime Organization (IMO). For this feasibility study The Ocean Cleanup assumes that platforms will not be flagged by a state and will thus not be subject to state law. The question remains if the UN would have some jurisdiction over the platforms, either by flagging or otherwise.

Third, as the Ocean Cleanup Project has the objective of passive collection of floating plastic waste, it would not qualify as a fishing activity. Therefore it does not fall under the current bycatch laws or the laws addressing "taking" of endangered migratory species. While assessing that The Ocean Cleanup bycatch will likely be minimal, the mere prospect of bycatch might bring The Ocean Cleanup into the realm of regulatory oversight.

Last, a proposal for a legal framework is postulated for international ocean rehabilitation projects.

FINANCIALS

The Ocean Cleanup Array is estimated to be 33 times cheaper than conventional cleanup proposals per extracted mass of plastics. In order to extract 70 million kg (or 42%) of garbage from the North Pacific Gyre over 10 years, we calculated a total cost of 317 million euro.

In the calculations, a limited lifetime of 10 years is applied instead of a general economic lifetime (for most equipment 20 years). This is because projections indicate the mean amount of plastic mass will decrease with time. Thus, the average mass of plastic that will be collected per year will likely be lower than what has been calculated using the 10-year deployment time. As expected with the passive cleanup concept, capital expenditures outweigh the operating expenditures. The total annual estimated operating expenditures is estimated at five million euro.

A break-even cost of €4.53 per kg of plastic collected must be realized in order for The Ocean Cleanup Array to be profitable (Figure 24). This amount falls in the range of beach cleanup costs, estimated to be €0.07 – €18.0 per kg. This is also less expensive than the plastic-caused damage to the maritime industry in the APEC region.

Based on the current estimates of costs and the amount of plastic in the oceans, the costs outweigh the profits generated by high-volume solutions, like incineration or pyrolysis, but it is unknown what the financial prospective would be for mechanical recycling. This should be investigated in a later phase.

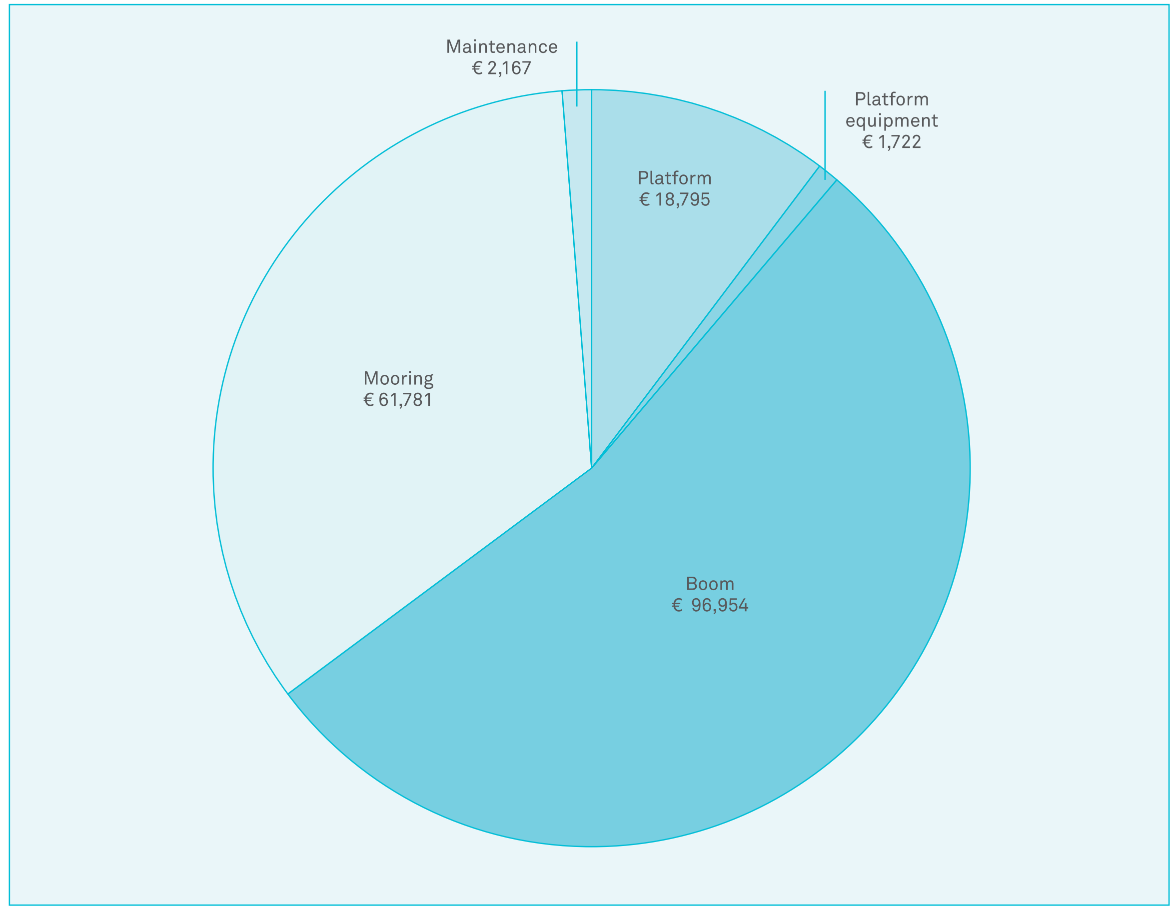


Figure 20 Estimated initial Base Capital Expenditure in euro '000s

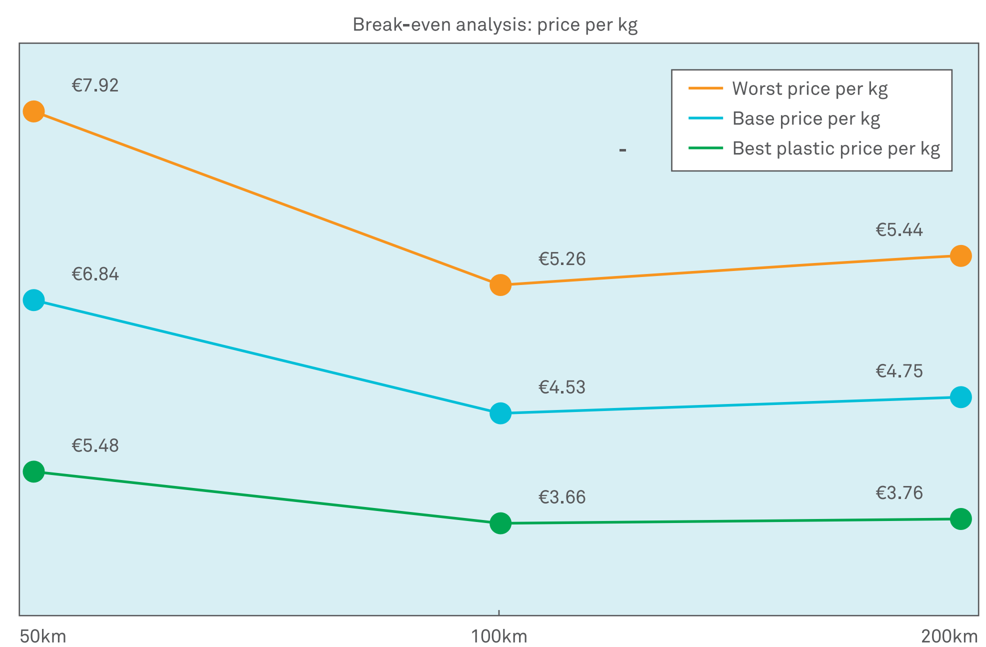
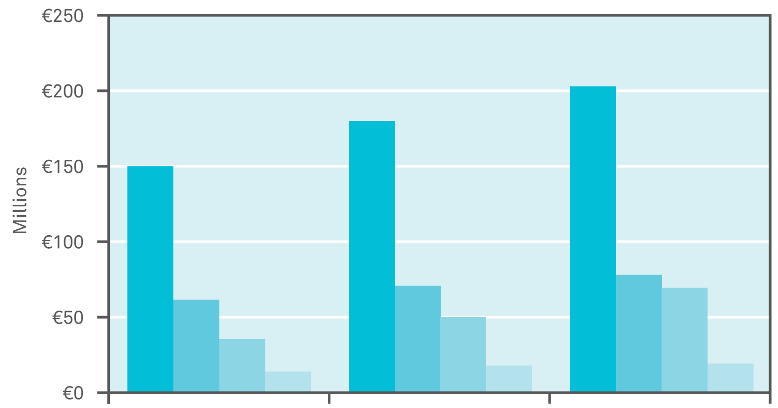


Figure 21 Break-even analysis in price per kg for each Array length in km.



	Best	Base	Worst
Initial Capital Expenditure	€ 147,984,453	€180,193,050	€202,684,608
CapEx Replacement Costs after 5 yrs	€ 61,035,640	€70,198,000	€ 78,191,390
Operating Expenditures over 10 yrs	€ 34,276,271	€ 49,997,283	€ 68,860,495
Decommissioning cost after 10 yrs	€ 12,607,500	€ 16,810,000	€ 18,491,000
Total Cost over 10 yrs Including Replacement & Decommissioning Costs	€ 255,903,864	€ 317,198,333	€ 368,227,492

Figure 22 OpEx in relation to CapEx, euro (best-, base-, and worst-case) over ten years.

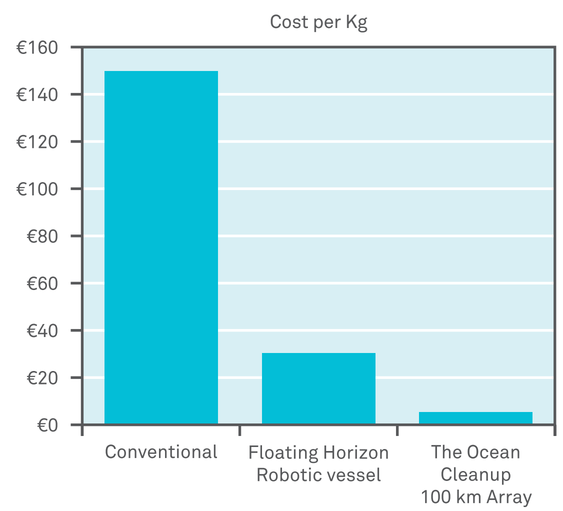


Figure 23 A comparison of cleanup costs per concept per kg

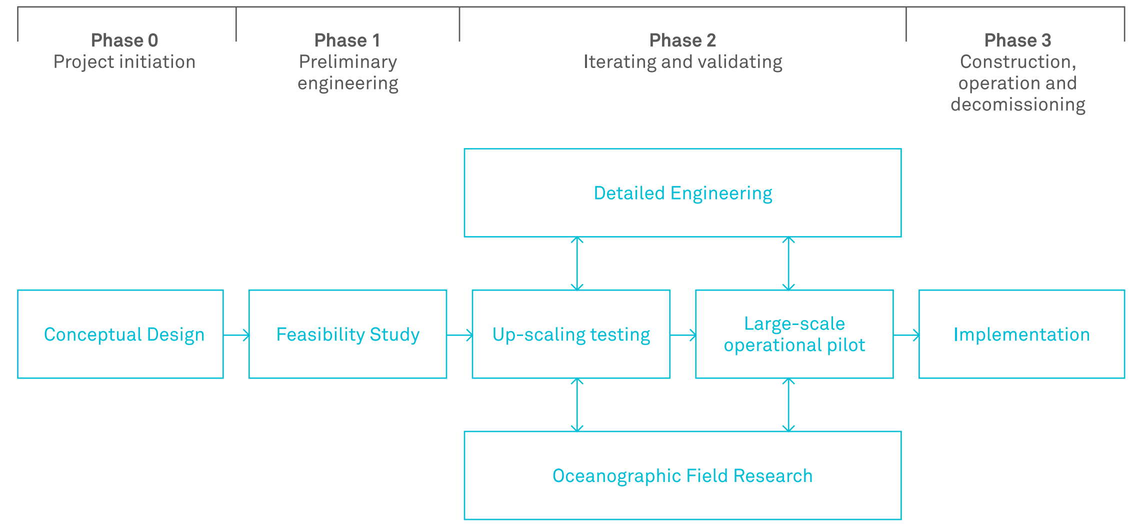


Figure 24 Phasing of The Ocean Cleanup project

LOOKING AHEAD

To address the remaining uncertainties identified in the feasibility study, a second phase of the project is proposed to prepare for implementation. In this phase, The Ocean Cleanup will develop a series of up-scaling tests, working towards a large-scale operational pilot in 3 to 4 years.

The scale of these tests will likely range from ~10m at the scale model test (1:1000) to ~10km for the large-scale operational test (1:10). Besides assessing new engineering results in a real-world environment, these tests also serve to uncover any unforeseen interactions between the structure and the environment, while allowing for the practicing of operational procedures.

In terms of research, the two essential elements in the second phase of the project are:

1 The in-depth engineering and optimization of the structure;
2 Improving the plastic mass estimate, by taking spatial and temporal variability, as well as measured vertical distribution into account.

To be more cost-efficient, The Ocean Cleanup will act as a facilitator of the research, outsourcing most of the fundamental research to institutes, and collaborating with offshore and engineering companies to cover most of the tests' costs.

CONCLUSIONS

Based on this collected evidence, it is concluded that The Ocean Cleanup Array is likely a feasible and viable method for large-scale, passive and efficient removal of floating plastic from the Great Pacific Garbage Patch.

However, for this project to be successful in reducing the amount of plastics in the Great Pacific Garbage Patch, it is essential for the influx of new plastic pollution into the oceans to be radically reduced.