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TECHNICAL PATHWAY TO THE
SUSTAINABILITY OF OUR
SEAS TO FACILITATE A
REGENERATIVE WORLD:
RESOURCES AND WASTE,
FOOD AND ENJOYMENT

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DOCTORAL THESIS

TECHNICAL PATHWAY TO THE SUSTAINABILITY OF OUR SEAS TO FACILITATE A REGENERATIVE WORLD: RESOURCES AND WASTE, FOOD AND ENJOYMENT

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ACRONYMS

ALARA: As Low As Reasonably Achievable
BAT: Best Available Techniques
BREFs: Best available techniques Reference document
CE: Circular Economy
CFs: Characterization Factors
DALY: Disability-Adjusted Life Years
DFAD: Drifting Fishing Aggregating Devices
EAP: Environmental Action Plans
EF: Emission Factor
EIPPCB: European IPPC Bureau
ELV: Emission Limit Values
EPS: Expanded polystyrene
FAD: Fish Aggregating Devices
FAO: Food and Agriculture Organization
FECYT: Foundation for Science and Technology
FOBs: Floating Objects
FRP: Fibre Reinforced Polymer
FSC: Free School Fishing
FTIR: Fourier Transform Infrared
GHG: Greenhouse Gas
HDPE: High Density Polyethylene
IA: Impact Assessment
ICCAT: International Commission for the Conservation of Atlantic Tuna
IED: Industrial Emissions Directive
IF: Improvable Flows
IMO: International Maritime Organization
IPPC: Integrated Pollution Prevention and Control regulation
IS: Impact Score
IUU: Illegal, Unreported and/or Unregulated fishing
LCA: Life Cycle Analysis
LCIA: Life Cycle Impact Assessment
LCT: Life Cycle Thinking
LDEP: Low Density Polyethylene
LNG: Low Nitrogen Content Fuel
MARPOL: Marine Pollution
MEFA: Material and Energy Flows Analysis
MFA: Material Flow Analysis
MFAD: Moored Fishing Aggregating Devices
MSC: Marine Stewardship Council
MTD: Mejores Técnicas Disponibles
PAF: Affected Fraction
PBAT: Poly (butylene adipate-co-terephthalate)
PBS: Polybutylene succinate

PBSA: Poly-(butylene succinate-co adipate)
PBSAT: Poly (butylene adipate-co-terephthalate)
PDF: Potentially Disappeared Fraction
PE: Polyethylene
PET or PETE: polyethylene terephthalate
PHBV: Poly-(3-hydroxybutyrate-co-3-hydroxyvalerate)
PLA: Polylactic acid
PLC: Polymers like poly- ϵ -caprolactone
PM: Particulate Matter
PP: Polypropylene
PRIORITY: Plastics monitoring detection Remediation recovery
PS: Polystyrene
PU: Polyurethane
PVC: Polyvinyl chloride
RFMOs: Regional Fisheries Management Organizations
RIC: Identification Coding System
SDG: Sustainable Development Goals
SME: Small and Medium-sized Enterprises
TC: Transfer Coefficient
TOC: Total Organic Compounds
UN: United Nations
UNCLOS: United Nations Convention on the Law of the Sea
UNEP: United Nations Environment Program
UNFCCC: United Nations Framework Convention on Climate Change
VOC: Volatile Organic Compounds
WOS: Web Of Science
WWF: World Wildlife Fund
WWTP: Wastewater Treatment Plant
ZEE: Zone Exclusive Economic

SUMMARY

The ocean occupies three quarters of the Earth's surface, it forms the most important ecosystem on the planet, housing the largest number of species that exist. It provides human beings with services as important as food, transportation, communication or the treatment of diseases, in addition to being key in climate regulation. For this reason, economic activity in the oceans is growing, increasing the pressure to which the ocean is subjected. Poor management of this wealth causes excessive exploitation of species, pollution, loss of habitats that will lead to an increase in climate change, among other problems, without forgetting the limitation that it will pose for the development of the economy. Faced with this challenge, there is an urgent need to achieve a cleaner ocean, reducing environmental pressures associated with the industry and human activities developing an innovative approach that promotes economic prosperity and environmental preservation.

Concern for environmental conservation and the creation of the first environmental policies has arisen since 1949, when the depletion of natural resources was discussed at the UN Conference on Conservation and Use of Resources in New York. Since this date, meetings and conferences have been held until today in which concern for the environment is increasing, specifically in the marine field. On the other hand, in the European Union in parallel and in response to the UN objectives, the Environmental Framework Programs are created. These are action plans that guide the environmental policies of Member States and they are important tools ensuring effective environmental management. Based on the objectives set by these EU framework programs; regulations are being created to protect the environment. Currently, the “VIII Environmental Action Program”, as a consequence of the previous ones, contributes to the transition towards a circular and regenerative economy, presenting itself as a solution to reduce this pressure. The IPPC (Integrated Pollution Prevention and Control) is one of the most important directives to minimize the environmental impacts of industrial activity, which gives rise to tools based on industrial ecology and life cycle thinking such as Material and Energy Flow Analysis (MEFA) or BAT Analysis (Best Available Techniques).

The main objective of this thesis is to contribute to the identification of sustainable techniques to facilitate the path towards a regenerative economy. Through a life cycle approach, human activities related to the sea as a provider of food raw materials and as a host for recreational activities are analysed. The specific objectives of this thesis are divided into three parts.

The first part, which is made up of two chapters, deals with fish and seafood transformation activities. Fish and seafood transformation activities are an important point in the consumption of ocean resources. Due to this and the great scope of this sector in Galicia, it is important to apply techniques that allow sustainable use of marine resources. These activities generate a large amount of waste that is difficult to manage, such as mussel shells. Although there are plants that use waste as a recovery process, odour emissions into the atmosphere become a problem. Therefore, the second objective of the first part is to identify the sources of pollution caused by this plant and find solutions and options for odorous emissions.

In CHAPTER 4, an octopus processing plant located in Galicia (NW Spain) is evaluated. The capture of this species is of great importance, appreciated for its great culinary value, not only in Galicia, but in the rest of the world to which a large quantity is exported. Octopus fishing has a great impact on the ocean, but we must also add the impact of its subsequent processing

in plants like the one chosen. Due to this importance, the need arises to address the study of the environmental aspects of this activity in order to establish strategies that minimize environmental impacts. The objective of this chapter is to apply the tools developed and known under the philosophy of Life Cycle Thinking: the calculation of the carbon footprint generated by the company, is added to the Material and Energy Flow Analysis (MEFA) and the analysis of Best Available Techniques (BAT). The calculation of the carbon footprint will indicate the CO₂ equivalent per flow, thus completing the MEFA in the identification of flows susceptible to improvement. The purpose of this chapter is to address and understand the use of these techniques in a simple way to combine them with others and seek other more complex results in the following chapters, to reduce the Environmental Impacts generated. To apply the tools, the first step is the identification of the case study. The plant is qualitatively analysed very exhaustively. The different operations and processes are identified, the materials that enter and the waste that leaves, in addition to the flows that exist throughout the process. Once the plant has been completely described, the MEFA is carried out. This is a quantitative analysis of the process, where the quantities of materials and consumption that enter and products that leave, as well as the waste generated, are collected. The next step is to calculate the consumption of electricity, water and diesel per ton of processed octopus for the different processes. In addition, the carbon footprint of each flow is calculated, thus completing the data of the flows to improve in the process. As a result, it is obtained that the flows of diesel, electricity and water are very important within the processing. To reduce these flows, forty-two best techniques are observed in the BREFs, of which twelve are already implemented. Therefore, this plant has a completion rate of 28%. Although this percentage is not too high, it is expected that the company has increased the number of techniques implemented. On the other hand, the application of this methodology provides effective solutions to the transformation of octopus, making it a more sustainable process.

CHAPTER 5 deals with the problem of waste generated by mussel shells, a great problem in Galicia (northwest Spain). Recent waste regulations and strategies open new opportunities for sustainable development through the management and treatment of aquaculture materials, previously considered waste. They promote the recovery of waste and its use as raw material so that resource consumption is reduced and sources of pollution are minimized. This chapter presents a plant that treats mussel shell waste as an input for its recovery process, which is a priori considered an ecological solution for the disposal of these products. This is a clear procedure to convert waste into a high added value product such as lime, a secondary but sustainable raw material with market potential to be used in different applications. However, as a result of the heat treatment of shell waste, odour emissions into the atmosphere become a serious problem. The pollution caused by these odours produces an environmental and social conflict between the plant and the surrounding population. Consequently, our work aims to identify the sources of pollution to find solutions to the facility's odorous emissions. To do this, the first step is the description of the process in the plant. Once described, an olfactometric analysis is carried out to detect the flows that could be improved and finally a series of solutions are presented as better techniques that allow reducing the odorous flows that expose the problem. Despite the variety of prevention and mitigation alternatives proposed, Odor problems are best addressed at their source, by designing or modifying the process, or even managing the activity differently (UKEPA, 2002). Therefore, the best odour management program for the process analysed, the valorisations of mussel shells, should include a complete redesign of the process, taking into account the conclusions drawn from this chapter, which indicated thermal treatments as the most odorous followed for the storage of raw materials.

The results of the first part conclude that the implementation of these sustainable techniques that are under the approach of life cycle thinking, helps to improve the flows that cause the potential impacts to the environment. The application of these techniques in one of the most important sectors of the Galician industry, such as the transformation of fish and seafood, both to the processing of the resource and the recovery of its waste, is of great importance to obtain a more sustainable activity.

The second part focuses on activities related to the fishing sector. The most relevant activity in the ocean is fishing, and tuna fishing is one of the most important fisheries due to its commercial value. This type of fishing generates great impacts on the environment. For this reason, and due to its great socioeconomic impact in Galicia, fishing is analysed in the field of industrial ecology, and more sustainable configurations for a tuna seiner are identified. The fishing sector is an activity of great importance in the world that generates a large amount of waste in the sea. Additionally, there are fisheries, such as tuna purse seine fisheries, that use fishing devices called FADs (Fish Aggregating Devices) to group fish. FADs are often discarded at sea and they are often made from non-biodegradable materials. For this reason, to contribute to the knowledge about these devices, about the materials used for their manufacture and to search for other materials that can be used as FAD, a systematic review of the literature is carried out. This helps us search for a biodegradable material that meets the necessary characteristics to be FAD or fishing net. Thus, it will avoid the abandonment of non-biodegradable waste in the ocean.

CHAPTER 6 analyses fishing as one of the most important marine activities, causing the two main threats to the marine environment, overfishing and marine pollution. In this context, the objective of this chapter is to investigate and validate methodologies for the identification of more sustainable operational configurations for a tuna seiner. The proposed methodology is based on a previous one applied to secondary industrial systems, taking into account the Integrated Pollution Prevention and Control (IPPC) approach, developed for the most potentially polluting industrial sources. The idea is to apply the same type of methodologies and concepts used for secondary industrial point sources, to a primary industrial mobile activity. This methodology combines two tools: "Analysis of materials and energy flows" (an industrial metabolism tool) and "Analysis of best available techniques." The first, provides a way to detect "improvable flows" in the system, and the second provides a way to define sustainable options for improvement. In the selected case study, five main flows that could be improved in the activity of a purse seine vessel were identified, most of them related to energy consumption and air emissions at different stages of the fishing activity. Thirty-one Best Available Techniques were inventoried for the system, which could potentially improve the sustainability of the activity. Seven of them have not yet been implemented in the case study. The possible improvements to the system proposed in this chapter are related to energy efficiency, waste management, prevention and control of atmospheric emissions. This methodology proves to be a good tool for sustainable point systems, but also for sustainable mobile systems, such as fishing activity in the oceans, as validated in the tuna seiner. The practical application of the identified technologies to fishing systems will contribute to the prevention and reduction of marine pollution, one of the greatest threats to today's oceans.

CHAPTER 7 studies fish aggregation devices, FAD, which are very common in tuna seiners. The tuna purse seine fishery is one of the largest in the world, using approximately 100,000 FAD per year, many of which are lost and abandoned. They are currently manufactured with plastic materials that cause environmental impacts in the ocean. Regional Fisheries Organizations (RFMOs) try to manage the large number of these devices deployed at sea, although this is a permanent problem. Due to the importance of FADs in the sea, their great

impacts and with the aim of finding solutions to the problem, a systematic review of the literature is carried out through the “Spanish Foundation for Science and Technology” (FECYT). The publications are grouped into eight categories where it is observed that, although most of the research focuses on “Animal Behaviour”, the most current topics are research in relation to the “Impacts” caused and the management of these devices. Although the topic “Biodegradable nets” turned out to be very little studied, it was considered important as a solution to the impacts caused by FADs. Therefore, four possible types of biodegradable materials have been identified, PHB being the most stand out. This material can be manufactured from tropical fruit waste generated in large plantations. Therefore, an exhaustive investigation into the production of PHB from food waste would be the next step in this analysis, since it would reduce the impact generated by waste both in the sea and in the food industry, also contributing to the circular economy.

The results of the second part conclude that it is necessary to intervene in the fishing sector both to improve the process of obtaining resources from the sea and to reduce the waste that is generated and dumped into the ocean. Thus, the techniques applied in Chapter 6 reduce the impacts generated by fishing boats and the study and search for biodegradable materials that replace conventional materials will reduce the discharges generated by fishing nets and devices that help the activity, contributing to prevent and reduce marine pollution from them.

The third part analyses those activities around the sea as a place of recreation and the plastic waste that is derived from these and all previous activities. Activities such as surfing require the construction of materials (surfboards) that generate a great impact. As the manufacturing of surfboards can be extrapolated to the manufacturing of small marine equipment that uses the same materials, techniques focused on the circular economy are developed, applied and validated with the aim of building a more sustainable marine equipment production model. All of these activities described above are some sources of plastics in the sea. Plastics in the sea are an important waste that generates a great impact on the ocean. The last objective of this part is to contribute to the knowledge of the sources and sinks that generate a great impact on the ocean, as well as their transformations and plastic waste management strategies. Finally, a flow analysis is carried out dynamically, through the modelling of flows and stocks, and a multimedia model is developed and applied that predicts the behaviour of the trends of these compounds.

CHAPTER 8 analyses the process of both manufacturing and using surfboards. Today, a radical revolution in the productive sphere is possible thanks to policies to combat the environmental crisis and technological progress, such as the Circular Economy. Recreational activities at sea are anthropogenic activities that have a potential impact, not only on the marine environment in the use phase (e.g. microplastics) and at the end of its useful life (e.g. ocean plastic waste), but also in the manufacturing phase, let's say throughout its life cycle. This last stage is also the most important to prevent and/or reduce impacts through, for example, eco-design. This chapter aims to analyse the marine equipment manufacturing sector using fibre reinforced polymers (which potentially emit VOCs with consequent toxicological impact) from a circular economy perspective to identify sustainable solutions for the manufacturing process phase. The selected case study is a marine equipment workshop that uses a fibre reinforced polymer. A previously validated methodology for the identification of sustainable industrial systems is modified, adapted and applied to this case. The methodology applies three tools: Analysis of Material and Energy Flows to identify the Improvable Flows (IF) of the process, Analysis of the Best Available Techniques (BAT), to propose the most appropriate techniques that improve these flows. Finally, an Impact Analysis (IA) was conducted to evaluate and compare the effects on humans and ecosystems in both the case study and enhanced scenarios.

Ten improvable flows were identified for the process and, consequently, fifteen candidates for Best Available Techniques were proposed with the objective of acting on said flows. The application of these techniques in an improved system allows reducing the amount of material and emissions, reducing the impact. The combination of these tools has been confirmed as a very good option for evaluating processes taking into account sustainability criteria. The impact assessment made it possible to compare the base scenario that shows a reduction in impacts through the best available techniques selected.

CHAPTER 9 contributes to knowledge of the sources and sinks of plastic in the ocean, as well as its transformations and management strategies. Currently, between 60% and 80% of trash is plastic, and almost 10% ends up directly or indirectly in the ocean. Plastics often undergo photooxidation producing microplastics. These microplastics derived from the breakdown of larger plastics are called secondary microplastics, which cannot simply be extracted from the oceans and, once mixed, enter the food chain and can have toxic effects. This chapter reviews the current information available on the topic in the scientific literature. Next, current strategies for managing plastic in the marine environment are analysed, with the aim of identifying possible needs and improvements from a sustainable point of view, and defining new approaches. In parallel, an analysis of material flows in different marine environments is carried out using system dynamics. A preliminary model of plastic mobilization in the ocean to other media in the marine environment (such as sediments and biota) is developed and validated with existing data from previous steps of the chapter. This chapter expands current knowledge on the management of plastics, their transformations and accumulation in the marine environment and the harmful effects on it. In addition, a preliminary dynamic model of plastic mobilization in the ocean is implemented, executed and validated. The developed model can be used to predict trends in the distribution of plastics in the ocean over time. In addition, you can see the most important plastic deposits in the ocean. Although plastics undergo transformations in the marine environment, it is not a means of disposal since most of them are not biodegradable. Most plastics accumulate at the bottom of the sea. The proportion of microplastics found in sediments is greater than that of macroplastics.

The results of the third part conclude that once again those of these sustainable techniques that are under the life cycle thinking approach are appropriate to contribute to a decrease in environmental impact. Furthermore, the importance of good management of plastics in all activities is reaffirmed so that they do not end up in the sea and the food chain.

Finally, it is observed that the tools used in each chapter are valid to minimize the impacts generated by human activities related to the sea. Furthermore, all chapters contribute to a greater or lesser extent to the regenerative economy. On the one hand, they help reduce the impacts generated by the fishing sector and the processing of its products, which helps to use resources extracted from the sea in a more sustainable way. On the other hand, the analysis of enjoyment activities is essential to reduce the impact on both the manufacture and use of recreational equipment, and can be extrapolated to any marine equipment manufactured with the same material. Finally, the analysis of the recovery of waste generated in the food industry, the knowledge of the materials that cause the most waste in fishing (nets) and the prediction of the movement of plastics in the sea, provide information that allows us to anticipate and minimize the problem of marine pollution. Therefore, this thesis contributes to protecting and obtaining a cleaner and more sustainable ocean.

RESUMEN

El océano ocupa las tres cuartas partes de la superficie terrestre, forma el ecosistema más importante del planeta, albergando la mayor cantidad de especies que existen. Proporciona al ser humano servicios tan importantes como la alimentación, el transporte, la comunicación o el tratamiento de enfermedades además de ser clave en la regulación climática. Por este motivo la actividad económica en los océanos está creciendo, aumentando la presión a la que está sometido el océano. Una mala gestión de esta riqueza provoca la explotación excesiva de especies, contaminación, pérdida de hábitats que derivarán en el aumento del cambio climático, entre otros problemas, sin olvidar la limitación que supondrá para el desarrollo de la economía. Frente a este desafío, existe una necesidad urgente de lograr un océano más limpio, reduciendo las presiones ambientales asociadas con la industria y las actividades humanas desarrollando un enfoque innovador que promueva la prosperidad económica y la preservación del medio ambiente.

La preocupación por la conservación del medio ambiente y la creación de las primeras políticas ambientales surge desde 1949, cuando se discutió el agotamiento de los recursos naturales en la Conferencia de la ONU sobre conservación y uso de los recursos en Nueva York. Desde esta fecha se han celebrado reuniones y jornadas hasta la actualidad en las que la preocupación por el medio ambiente es cada vez mayor, concretamente en el ámbito marino. Por otro lado, en la Unión Europea en paralelo y en respuesta a los objetivos de la ONU, se crean los Programas Marco Ambientales. Se trata de planes de acción que guían las políticas medioambientales de los Estados miembros y son herramientas importantes que garantizan una gestión medioambiental eficaz. A partir de los objetivos fijados por estos programas marco de la UE, se están creando regulaciones para proteger el medio ambiente. En la actualidad, el VIII Programa de Acción Ambiental en consecuencia de los anteriores contribuye a la transición hacia una economía circular y regenerativa, presentándose como una solución para reducir esta presión. El IPPC (Prevención y Control Integrado de la Contaminación) es una de las directivas más importantes para minimizar los impactos ambientales de la actividad industrial, lo que da lugar a herramientas basadas en la ecología industrial y el pensamiento del ciclo de vida como el Análisis de Flujos de Materia y Energía (MEFA) o Análisis BAT (Mejores Técnicas Disponibles).

El principal objetivo de esta tesis es contribuir a la identificación de técnicas sostenibles para facilitar el camino hacia una economía regenerativa. A través de un enfoque de ciclo de vida, se analizan las actividades humanas relacionadas con el mar como proveedor de materias primas alimentarias y como lugar de acogida de actividades de recreo. Los objetivos específicos de esta tesis se dividen en tres partes.

La primera parte, que se compone de dos capítulos, trata de aquellas actividades de transformación de pescados y mariscos. Las actividades de procesamiento de pescados y mariscos son un punto importante en el consumo de recursos oceánicos. Debido a esto y al gran alcance de este sector en Galicia, es importante aplicar técnicas que permitan un uso sostenible de los recursos marinos. Estas actividades generan una gran cantidad de residuos de difícil gestión, como las conchas de mejillón. Aunque hay plantas que aprovechan los residuos como proceso de valorización, las emisiones de olores a la atmósfera se convierten en un problema. Por tanto, el segundo objetivo de la primera parte es identificar las fuentes de contaminación provocadas por esta planta y encontrar soluciones y opciones para las emisiones olorosas.

En el CAPÍTULO 4 se evalúa una planta procesadora de pulpo ubicada en Galicia (Noroeste de la Península Ibérica). La captura de esta especie es de gran importancia, apreciada por su gran valor culinario, no sólo en Galicia, sino en el resto del mundo al que se exporta una gran cantidad. La pesca del pulpo tiene un gran impacto en el océano, pero también hay que añadir el impacto de su posterior procesamiento en plantas como la elegida. Debido a esta importancia surge la necesidad de abordar el estudio de los aspectos ambientales de esta actividad con el fin de establecer estrategias que minimicen los impactos ambientales. El objetivo de este capítulo es aplicar las herramientas desarrolladas y conocidas bajo la filosofía del Life Cycle Thinking: al Análisis de Flujos de Materia y Energía (MEFA) y al análisis de Mejores Técnicas Disponibles (BAT) se añade el cálculo de la huella de carbono generada por la empresa. El cálculo de la huella de carbono indicará el CO₂ equivalente por flujo, completando así el MEFA en la identificación de flujos susceptibles de mejora. El propósito de este capítulo es abordar y comprender el uso de estas técnicas de forma sencilla para combinarlas con otras y buscar otros resultados más complejos en los siguientes capítulos, para la reducción de los Impactos Ambientales generados. Para aplicar las herramientas, el primer paso es la identificación del caso de estudio. La planta se analiza de forma cualitativa muy exhaustivamente. Se identifican las diferentes operaciones y procesos, los materiales que entran y los residuos que salen, además de los flujos que existen a lo largo del proceso. Una vez descrita completamente la planta se procede a realizar el MEFA. Se trata de un análisis cuantitativo del proceso, donde se recogen las cantidades de materiales y consumos que entran y productos que salen, así como los residuos generados. El siguiente paso es calcular el consumo tanto de electricidad, agua y diésel por tonelada de pulpo procesado para los diferentes procesos. Además, se calcula la huella de carbono de cada flujo, completando así los datos de los flujos a mejorar en el proceso. Como resultado se obtiene que los flujos de diésel, electricidad y agua son muy importantes dentro del procesamiento. Para reducir estos flujos se observan cuarenta y dos mejores técnicas disponibles en los BREF, de las cuales doce ya están implementadas. Por tanto, esta planta tiene un grado de ejecución del 28%. Aunque este porcentaje no es demasiado alto, se espera que la empresa haya aumentado el número de técnicas implementadas. Por otro lado, la aplicación de esta metodología brinda soluciones efectivas a la industria del pulpo, convirtiéndola en un proceso más sostenible.

El CAPÍTULO 5 trata el problema de los residuos generados por las conserveras de mejillón, un problema importante en Galicia (noroeste de España). Las recientes regulaciones y estrategias sobre residuos abren nuevas oportunidades para el desarrollo sostenible a través de la gestión y el tratamiento de materiales de la acuicultura, antes considerados residuos. Fomentan la valorización de los residuos y su uso como materia prima de manera que se reduzca el consumo de recursos y se minimicen las fuentes de contaminación. Este capítulo presenta una planta que trata los residuos de cáscara de mejillón como insumo para su proceso de valorización, lo que a priori se considera una solución ecológica para la eliminación de estos productos. Se trata de un procedimiento claro para convertir residuos en un producto de alto valor añadido como es la cal, una materia prima secundaria pero sostenible y con potencial de mercado para ser utilizada en diferentes aplicaciones. Sin embargo, como resultado del tratamiento térmico de los residuos de conchas, las emisiones de olores a la atmósfera se convierten en un problema grave. La contaminación provocada por estos olores produce un conflicto ambiental y social entre la planta y la población circundante. En consecuencia, nuestro trabajo tiene como objetivo identificar las fuentes de contaminación para encontrar soluciones a las emisiones olorosas de la instalación. Para ello, el primer paso es la descripción del proceso en la planta. Una vez descrito se realiza un análisis olfatométrico para detectar los flujos mejorables y finalmente se presentan una serie de soluciones como mejores técnicas que

permiten reducir los flujos olorosos que exponen el problema. A pesar de la variedad de alternativas de prevención y mitigación propuestas, los problemas de olores se abordan mejor en su origen, mediante el diseño o modificación del proceso, o incluso gestionando la actividad de manera diferente (UKEPA, 2002). Por tanto, el mejor programa de gestión de olores para el proceso analizado, la valorización de la cáscara de mejillón, debería incluir un rediseño completo del proceso, teniendo en cuenta las conclusiones extraídas de este capítulo, que señalaban los tratamientos térmicos como los más olorosos seguidos. para el almacenamiento de materias primas.

Los resultados de la primera parte concluyen que la implementación de estas técnicas sostenibles que están bajo el enfoque del pensamiento de ciclo de vida, ayuda a mejorar los caudales que causan más impactos al medio ambiente. La aplicación de estas técnicas en uno de los sectores más importantes de la industria gallega, como es la transformación de pescados y mariscos, tanto al procesamiento del recurso como a la valorización de sus residuos, es de gran importancia para obtener una actividad más sostenible.

La segunda parte se centra en las actividades relacionadas con el sector pesquero. La actividad más relevante en el océano es la pesca, y la pesca del atún es una de las pesquerías más importantes por su valor comercial. Este tipo de pesca genera grandes impactos en el medio ambiente. Por ello, y por su gran impacto socioeconómico en Galicia, la pesca se analiza en el ámbito de la ecología industrial, y se identifican configuraciones más sostenibles para un cerquero atunero. El sector pesquero es una actividad de gran importancia en el mundo que genera una gran cantidad de residuos en el mar. Además, hay pesquerías, como la del atún con red de cerco, que utilizan dispositivos de pesca llamados FAD (Dispositivos de Agregación de Peces, por sus siglas en inglés) para agrupar peces. Los FAD suelen desecharse en el mar y suelen estar fabricados con materiales no biodegradables. Por este motivo, para contribuir al conocimiento sobre estos dispositivos, sobre los materiales utilizados para su fabricación y buscar otros materiales que puedan ser utilizados como FAD, se realiza una revisión sistemática de la bibliografía. Esto nos ayuda a buscar un material biodegradable que cumpla con las características necesarias para ser FAD o red de pesca. Así, evitaremos el abandono de residuos no biodegradables en el océano.

En el CAPÍTULO 6 se analiza la pesca como una de las actividades marinas más importantes, causante de las dos principales amenazas al medio marino, la sobrepesca y la contaminación marina. En este contexto, el objetivo de este capítulo es investigar y validar metodologías para la identificación de configuraciones operativas más sostenibles para un atunero cerquero. La metodología propuesta se basa en una anterior aplicada a sistemas industriales secundarios, teniendo en cuenta el enfoque de Prevención y Control Integrados de la Contaminación (IPPC), desarrollado para las fuentes industriales más potencialmente contaminantes. La idea es aplicar el mismo tipo de metodologías y conceptos utilizados para fuentes puntuales industriales secundarias, a una actividad móvil industrial primaria. Esta metodología combina dos herramientas: "Análisis de flujos de materiales y energía" (una herramienta de metabolismo industrial) y "Análisis de las mejores técnicas disponibles". El primero proporciona una manera de detectar "corrientes mejorables" en el sistema, y el segundo proporciona una manera de definir opciones sostenibles para mejorarlas. En el caso de estudio seleccionado se identificaron cinco principales flujos mejorables en la actividad de un cerquero, la mayoría de ellos relacionados con el consumo de energía y las emisiones al aire en diferentes etapas de la actividad pesquera. Se inventariaron treinta y una Mejores Técnicas Disponibles para el sistema, que potencialmente podrían mejorar la sostenibilidad de la actividad. Siete de ellos aún no se han implementado en el estudio de caso. Las posibles mejoras del sistema que propone este capítulo están relacionadas con la eficiencia energética, la gestión de residuos, la

prevención y el control de emisiones atmosféricas. Esta metodología demuestra ser una buena herramienta para sistemas de puntos sostenibles, pero también para sistemas móviles sostenibles, como la actividad pesquera en los océanos, como se validó en el atunero cerquero. La aplicación práctica de las tecnologías identificadas a los sistemas de pesca contribuirá a la prevención y reducción de la contaminación marina, una de las mayores amenazas a los océanos actuales.

En el CAPITULO 7 se estudian los dispositivos de agregación de peces, FAD, que son muy comunes en los atuneros cerqueros. La pesquería de atún con redes de cerco es una de las más importantes del mundo y utiliza aproximadamente 100,000 FAD al año, muchos de los cuales se pierden y abandonan. Actualmente se fabrican con materiales plásticos que provocan impactos ambientales en el océano. Las Organizaciones Regionales de Pesca (OROP) intentan gestionar el gran número de estos dispositivos desplegados en el mar, aunque se trata de un problema permanente. Debido a la importancia de los FAD en el mar, sus grandes impactos y con el objetivo de encontrar soluciones al problema, se realiza una revisión sistemática de la literatura a través de la “Fundación Española para la Ciencia y la Tecnología” (FECYT). Las publicaciones se agrupan en ocho categorías donde se observa que, si bien la mayoría de las investigaciones se centran en el “Comportamiento animal”, los temas de mayor actualidad son investigaciones en relación a los “Impactos” causados y el manejo de estos dispositivos. Aunque el tema “Redes biodegradables” resultó ser muy poco estudiado, se consideró importante como solución a los impactos causados por los FAD. Por lo tanto, se han identificado cuatro posibles tipos de materiales biodegradables, siendo el PHB el más destacado. Este material se puede fabricar a partir de residuos de frutas tropicales generados en grandes plantaciones. Por eso, una investigación exhaustiva sobre la producción de PHB a partir de residuos de alimentos sería el siguiente paso de este análisis, ya que reduciría el impacto que generan los residuos tanto en el mar como en la industria alimentaria, contribuyendo también a la economía circular.

Los resultados de la segunda parte concluyen que es necesario intervenir en el sector pesquero tanto para mejorar el proceso de obtención de recursos del mar como para reducir los residuos que se generan y vierten al océano. Así, las técnicas aplicadas en el Capítulo 6 reducen los impactos generados por los barcos pesqueros y el estudio y búsqueda de materiales biodegradables que sustituyan a los convencionales reducirá los vertidos generados por las redes de pesca y dispositivos que ayudan a la actividad, contribuyendo a prevenir y reducir la contaminación marina por estos.

La tercera parte analiza aquellas actividades en torno al mar como lugar de recreo y los residuos plásticos que se derivan de estas y todas las actividades anteriores. Actividades como el surf requieren de la construcción de materiales (tablas) que generen un gran impacto. Como la fabricación de tablas de surf es extrapolable a la fabricación de pequeños equipos marinos que utilizan los mismos materiales, se desarrollan, aplican y validan técnicas enfocadas a la economía circular con el objetivo de construir un modelo de producción de equipos marinos más sostenible. Todas estas actividades descritas anteriormente son algunas fuentes de plásticos en el mar. Los plásticos en el mar son un residuo importante que genera un gran impacto en el océano. El último objetivo de esta parte es contribuir al conocimiento de las fuentes y sumideros que generan un gran impacto en el océano, así como sus transformaciones y estrategias de gestión de residuos plásticos. Finalmente, se realiza un análisis de flujos de forma dinámica, mediante la modelización de flujos y stocks, y se desarrolla y aplica un modelo multimedia que predice el comportamiento de las tendencias de estos compuestos.

En el CAPÍTULO 8 se analiza el proceso tanto de fabricación como de uso de las tablas de surf. Hoy, una revolución radical en el ámbito productivo es posible gracias a políticas de lucha

contra la crisis ambiental y al progreso tecnológico, como la Economía Circular. Las actividades recreativas en el mar son actividades antropogénicas que tienen un impacto potencial, no sólo en el medio marino en la fase de uso (por ejemplo, microplásticos) y al final de su vida útil (por ejemplo, desechos plásticos del océano), sino también en la fase de fabricación, digamos a lo largo de su ciclo de vida. Esta última etapa es también la más importante para prevenir y/o reducir impactos mediante, por ejemplo, el ecodiseño. Este capítulo tiene como objetivo analizar el sector de fabricación de equipos marinos utilizando polímeros reforzados con fibra (que potencialmente emiten COV con el consiguiente impacto toxicológico) desde una perspectiva de economía circular para identificar soluciones sostenibles para la fase del proceso de fabricación. El caso de estudio seleccionado es un taller de equipos marinos que utiliza un polímero reforzado con fibra. Se modifica, adapta y aplica a este caso una metodología previamente validada para la identificación de sistemas industriales sostenibles. La metodología aplica tres herramientas: Análisis de Flujos de Materiales y Energía para identificar los Flujos Mejorables (FI) del proceso, Análisis de las Mejores Técnicas Disponibles (MTD), para proponer las técnicas más adecuadas que mejoren esos flujos. Finalmente, se realizó un Análisis de Impacto (IA) para evaluar y comparar los efectos sobre los humanos y los ecosistemas, tanto en el escenario del caso de estudio como en los mejorados. Se identificaron diez flujos mejorables para el proceso y, en consecuencia, se propusieron quince candidatas a Mejores Técnicas Disponibles con el objetivo de actuar sobre dichos flujos. La aplicación de estas técnicas en un sistema mejorado permite reducir la cantidad de material y emisiones reduciendo el impacto. La combinación de estas herramientas se ha confirmado como una muy buena opción para la evaluación de procesos teniendo en cuenta criterios de sostenibilidad. La evaluación de impacto permitió comparar el escenario base que muestra una reducción de los impactos mediante las mejores técnicas disponibles seleccionadas.

EL CAPÍTULO 9 contribuye al conocimiento de las fuentes y sumideros de plástico en el océano, así como de sus transformaciones y estrategias de gestión. Actualmente, entre el 60% y el 80% de la basura es plástico, y casi el 10% acaba directa o indirectamente en el océano. Los plásticos a menudo sufren fotooxidación produciendo microplásticos. Estos microplásticos derivados de la descomposición de plásticos más grandes se denominan microplásticos secundarios, que no pueden extraerse simplemente de los océanos y, una vez mezclados, entran en la cadena alimentaria y pueden tener efectos tóxicos. Este capítulo revisa la información actual disponible sobre el tema en la literatura científica. A continuación, se analizan las estrategias actuales de gestión del plástico en el medio marino, con el objetivo de identificar posibles necesidades y mejoras desde un punto de vista sostenible, y definir nuevos enfoques. Paralelamente, se lleva a cabo un análisis de los flujos de materiales en diferentes medios marinos mediante dinámica de sistemas. Se desarrolla y valida un modelo preliminar de movilización de plásticos en el océano hacia otros medios en el entorno marino (como sedimentos y biota) con datos existentes de pasos anteriores del capítulo. Este capítulo amplía el conocimiento actual sobre la gestión de los plásticos, sus transformaciones y acumulación en el medio marino y los efectos nocivos sobre el mismo. Además, se implementa, ejecuta y valida un modelo dinámico preliminar de movilización de plástico en el océano. El modelo desarrollado se puede utilizar para predecir tendencias en la distribución de plásticos en el océano a lo largo del tiempo. Además, se pueden observar los depósitos de plástico más importantes del océano. Aunque los plásticos sufren transformaciones en el medio marino, no es un medio de eliminación ya que la mayoría de ellos no son biodegradables. La mayoría de los plásticos se acumulan en el fondo del mar. La proporción de microplásticos que se encuentran en los sedimentos es mayor que la de macroplásticos.

Los resultados de la tercera parte concluyen que una vez más aquellas de estas técnicas sostenibles que están bajo el enfoque del pensamiento de ciclo de vida son adecuadas para contribuir a una disminución del impacto ambiental. Además, se reafirma la importancia de la buena gestión de los plásticos en todas las actividades para que no acaben en el mar y en la cadena alimentaria.

Para finalizar se observa que las herramientas utilizadas en cada capítulo son válidas para minimizar los impactos generados en las actividades humanas relacionadas con el mar. Además, todos los capítulos contribuyen en mayor o menor medida a la economía regenerativa. Por un lado, ayudan a reducir los impactos generados por el sector pesquero y el procesamiento de sus productos, lo que ayuda a utilizar los recursos extraídos del mar de una forma más sostenible. Por otro lado, el análisis de las actividades de recreo es fundamental para reducir el impacto tanto en la fabricación como en el uso de equipos recreativos, pudiéndose extrapolar a cualquier equipo marino fabricado con el mismo material. Finalmente, el análisis de la valorización de los residuos generados en la industria alimentaria, el conocimiento de los materiales que más residuos provocan en la pesca (redes) y la predicción del movimiento de los plásticos en el mar, aportan información que permite anticiparnos y minimizar el problema de la contaminación marina. Por tanto, esta tesis contribuye a proteger y obtener un océano más limpio y sostenible.

RESUMO

O océano ocupa as tres cuartas partes da superficie terrestre, conforma o ecosistema máis importante do planeta albergando o maior número de especies que existen. Proporciona ó ser humano de servizos tan importantes como alimentación, transporte, comunicación ou tratamentos para enfermidades ademais de ser clave na regulación climática. Por este motivo a actividade económica nos océanos é cada vez maior, aumentando a presión á que se somete o océano. Unha mala xestión de esta riqueza provoca a explotación excesiva de especies, contaminación, perda de hábitats que derivarán no aumento do cambio climático, entre outros problemas, por non falar da limitación que suporá para o desenvolvemento da economía. Ante este desafío urxe a necesidade de lograr un océano máis limpo, reducindo as presións ambientais asociadas á industria e ás actividades humanas para desenvolver un enfoque innovador que promova a prosperidade económica e a preservación ambiental.

A preocupación pola conservación do medio ambiente e pola creación das primeiras políticas ambientais xorde dende 1949 cando xa se falaba do esgotamento dos recursos naturais na Conferencia da ONU sobre a conservación e utilización dos recursos en Nova York. A partir desta data foron realizándose reunións e conferencias ata día de hoxe nas que a preocupación polo medio ambiente cada vez é maior en concreto no ámbito mariño. Por outra banda, na Unión Europea de maneira paralela e en resposta ós obxectivos da ONU, créanse os Programas Marco do Medio ambiente. Estes, son plans de acción que guían ás políticas dos Estados Membros en materia de medio ambiente e son ferramentas importantes que garanten unha xestión ambiental efectiva. A partir dos obxectivos que marcan estes programas marco da UE, vanse creando normativas que protexan o medio ambiente. Na actualidade, o VIII Programa de Acción Ambiental en consecuencia cos anteriores contribúe á transición cara unha economía circular e rexenerativa, presentándose como unha solución para reducir esta presión. A IPPC (Prevención e Control Integrados da Contaminación) é unha das directivas máis importantes para minimizar os impactos ambientais da actividade industrial, da que xorden ferramentas baseadas na ecoloxía industrial e do pensamento de ciclo de vida como é o Análise de Fluxos de Materia e Enerxías (MEFA) ou MTD (Mellores Técnicas Disponibles) Análise.

O Obxectivo principal desta tese é contribuír á identificación de técnicas sostibles para facilitar o camiño cara unha economía rexenerativa. A través de un enfoque de ciclo de vida analízanse as actividades humanas relacionadas co mar como provedor de materias primas alimenticias e como lugar de acoillida de actividades de lecer. Os obxectivos específicos desta tese divídense en tres partes.

A primeira parte, que está composta por dous capítulos, ocúpase de aquelas actividades de transformación de peixes e mariscos. As actividades de transformación de peixes e mariscos son un punto importante no consumo de recursos oceánicos. Debido a isto e o gran alcance deste sector en Galicia, é importante aplicar técnicas que permitan un uso sostible dos recursos mariños. Estas actividades xeran unha gran cantidade de residuos difíciles de xestionar, como as cunchas de mexillón. Aínda que existen plantas que aproveitan os residuos como proceso de valorización, as emisións de olores á atmosfera convértese nun problema. Polo tanto, o segundo obxectivo da primeira parte é identificar as fontes de contaminación que provoca esta planta e buscar solucións e opcións para as emisións olorosas.

No CAPÍTULO 4 aválase unha planta procesadora de polbo situada en Galicia (Noroeste da Península Ibérica). A captura desta especie é de gran importancia, apreciada polo seu gran

valor culinario, non só en Galicia, senón no resto do mundo ó que se exporta unha gran cantidade. A pesca do polbo causa un gran impacto no océano, pero ademais hai que engadir o impacto do seu procesado posteriormente en plantas como a escollida. Debido a esta importancia xorde a necesidade de abordar o estudo dos aspectos ambientais desta actividade con fin de establecer estratexias que minimicen os impactos ambientais. O obxectivo deste capítulo é aplicar as ferramentas desenroladas e coñecidas baixo a filosofía do Pensamento de Ciclo de Vida: ó Análise de Fluxos de Materia e Enerxía (MEFA) e á análise de Melloras Técnicas Dispoñibles (MTD) engádese o cálculo da pegada de carbono xerada pola empresa. O cálculo da pegada de carbono, indicará o CO₂ equivalente por fluxo, completando así o MEFA na identificación dos fluxos mellorables. A finalidade deste capítulo é achegar e comprender o uso destas técnicas dunha maneira sinxela para combinalas con outras e buscar outros resultados máis complexos nos seguintes capítulos, para a diminución do Impactos Ambientais xerados. Para aplicación das ferramentas o primeiro paso é a identificación do caso de estudo. Analízase a planta dunha maneira cualitativa moi exhaustiva. Identifícanse as diferentes operacións e procesos, os materiais que entran e os residuos que saen, ademais dos fluxos que existen en todo o proceso. Unha vez a planta está completamente descrita realízase o MEFA. Esta é unha análise cuantitativa do proceso, onde recollen as cantidades de materiais e consumos que entran e produtos que saen, así como os residuos xerados. O seguinte paso é calcular os consumos tanto de electricidade, auga e diésel por tonelada de polbo procesado para diferentes procesos. Ademais calcúlase a pegada de carbono para cada fluxo, completando así os datos dos fluxos a mellorar no proceso. Como resultado obtense que os fluxos de diésel, electricidade e auga son moi importantes dentro do procesado. Para reducir estes fluxos obsérvanse cuarenta e dúas mellores técnicas dispoñibles nos BREF das cales doce xa están implementadas. Polo tanto, esta planta ten un grado de execución dun 28%. Aínda que este porcentaxe non é demasiado elevado, espérase que na actualidade a empresa haxa aumentado o número de técnicas implementadas. Por outra banda a aplicación desta metodoloxía aporta solucións efectivas á industria do polbo converténdoa nun proceso máis sostible.

No CAPÍTULO 5 abórdase a problemática dos residuos que xeran as conserveiras de mexillón, un gran problema en Galicia (Noroeste de España). As recentes normativas e estratexias en materia de residuos abren novas oportunidades para o desenvolvemento sostible mediante a xestión e o tratamento de materiais acuícolas, antes considerados residuos. Fomentan a valorización dos residuos e o seu uso como materias primas de forma que se reduza o consumo de recursos e se minimicen as fontes de contaminación. Neste capítulo preséntase unha planta que trata os residuos de cuncha de mexillón como entrada no seu proceso de valorización, que se considera a *priori* unha solución ecolóxica para a eliminación destes produtos. É un procedemento claro para converter os residuos nun produto de alto valor engadido como a cal, unha materia prima secundaria, pero sostible con potencial de mercado para ser utilizada en diferentes aplicacións. Non obstante, como resultado do tratamento térmico dos residuos de casca, as emisións de cheiros á atmosfera convértense nun grave problema. A contaminación provocada por estes cheiros produce un conflito ambiental e social entre a planta e a poboación da contorna. En consecuencia, o noso traballo pretende identificar as fontes de contaminación para buscar solucións ás emisións olorosas da instalación. Para elo o primeiro paso é a descrición do proceso na planta. Unha vez descrito realízase unha análise olfatómétrica para detectar os fluxos mellorables e por último preséntanse unha serie de solucións como mellores técnicas que permiten diminuír os fluxos olorosos que amosan o problema.

A pesar da variedade de alternativas de prevención e diminución propostas, os problemas de olores son mellor abordados en orixe, mediante o deseño ou modificación do proceso, ou mesmo xestionando a actividade de forma diferente (UKEPA, 2002). Por iso, o mellor

programa de xestión de olores para o proceso analizado, a valorización da cuncha de mexillón, debería incluír un completo re-deseño do proceso, tendo en conta as conclusións extraídas deste capítulo, que sinalou os tratamentos térmicos como os procesos máis olorosos, seguidos polo almacenamento de materias primas. Os resultados da primeira parte conclúen que a implantación destas técnicas sostíbles que están baixo o enfoque do pensamento do ciclo de vida axudan a mellorar os fluxos que máis impactos causan sobre o medio ambiente. A aplicación destas técnicas nun dos sectores máis importantes da industria galega como son as actividades transformadoras de peixe e mariscos, tanto ó procesado do recurso como á valorización dos seus residuos é de gran importancia para obter unha actividade máis sostíble.

A segunda parte enfócase nas actividades relacionadas co sector pesqueiro. A actividade máis relevante no océano é a pesca, e a pesca do atún é unha das pescas máis importantes polo seu valor comercial. Este tipo de pesca xera grandes impactos no medio ambiente. Por iso, e polo seu gran impacto socioeconómico en Galicia, a pesca analízase no ámbito da ecoloxía industrial, e identifícanse configuracións máis sostíbles para un buque atuneiro cerqueiro. O sector pesqueiro é unha actividade de gran importancia no mundo que xera unha gran cantidade de residuos no mar. Ademais, hai pescas, como a do atún con cerco, que utilizan dispositivos de pesca chamados FAD (Dispositivos de Agregación de Peixes, das súas iniciais en inglés) para agrupar peixes. Os FAD soen abandonarse no mar e normalmente están fabricados con materiais non biodegradables. Por este motivo, para contribuír ó coñecemento sobre estes dispositivos, ós materiais utilizados para a súa fabricación, e buscar outro material que poida ser utilizado como FAD realízase unha revisión sistemática da bibliografía. Isto axúdanos a buscar un material biodegradable que cumpra coas características necesarias para ser FAD ou rede de pesca. Así evitaremos o abandono de residuos non biodegradables no océano.

No CAPÍTULO 6 analízase a pesca como unha das actividades mariñas máis importantes, que causa as dúas principais ameazas para o medio mariño, sobrepesca e a contaminación mariña. Neste contexto, o obxectivo deste capítulo é investigar e validar metodoloxías para a identificación de configuracións operativas máis sostíbles para un barco cerqueiro atuneiro. A metodoloxía proposta baséase nunha anterior aplicada a sistemas industriais secundarios, tendo en conta o enfoque de Prevención e Control Integrado da Contaminación (IPPC), desenvolvido para as fontes industriais máis potencialmente contaminantes. A idea é aplicar o mesmo tipo de metodoloxías e conceptos empregados para fontes puntuais industriais secundarias, a unha actividade móbil industrial primaria. Esta metodoloxía combina dúas ferramentas: "Análise de fluxos de materiais e enerxía" (unha ferramenta do metabolismo industrial) e "Análise das mellores técnicas dispoñibles". O primeiro proporciona unha forma de detectar "Fluxos Mellorables" no sistema, e o segundo proporciona un xeito de definir opcións sostíbles para melloralos. No caso de estudo seleccionado identificáronse cinco principais fluxos mellorables na actividade dun cerqueiro, a maioría deles relacionados co consumo de enerxía e a emisión de aire en diferentes etapas da actividade pesqueira. Inventariáronse trinta e unha Mellores Técnicas Dispoñibles para o sistema, que potencialmente poderían mellorar a sustentabilidade da actividade. Sete deles aínda non están implementadas no estudo de caso. As posibles melloras do sistema que propón este capítulo están relacionadas coa eficiencia enerxética, a xestión de residuos, a prevención e control das emisións atmosféricas. Esta metodoloxía demostra ser unha boa ferramenta cara a sistemas puntuais sostíbles, pero tamén cara a sistemas móbiles sostíbles como a actividade pesqueira nos océanos, tal e como se valida no barco atuneiro do cerco. A aplicación práctica das tecnoloxías identificadas aos sistemas de pesca contribuirá a previr e reducir a contaminación mariña, unha das maiores ameazas dos océanos actuais.

No CAPÍTULO 7 estúdanse os dispositivos de agregación de peixes, FAD, moi habituais nos barcos de pesca de atún con cerco. A pesca do atún con cerco é unha das pesqueiras máis importantes do mundo e desprega aproximadamente 100,000 FAD ao ano, perdendo e abandonando moitos deles. Actualmente están fabricados con materiais plásticos que causan impactos ambientais no océano. As Organizacións Rexionais de Pesca tratan de xestionar o gran número destes aparellos despregados no mar, aínda que se trata dun problema permanente. Debido á importancia dos FAD no mar, aos seus grandes impactos e co obxectivo de buscar solucións ao problema, realízase unha revisión sistemática da literatura a través da Fundación Española para a Ciencia e a Tecnoloxía (FECYT). As publicacións agrúpanse en oito categorías onde se observa que, aínda que a maioría das investigacións se centran no comportamento animal, os temas máis actuais son a investigación en relación cos impactos provocados e a xestión destes dispositivos. Aínda que o tema "Redes biodegradables" resultou ser moi pouco estudado, considerouse importante como solución aos impactos que provocan os FAD. Polo tanto, identificáronse catro posibles tipos de materiais biodegradables, destacando o PHB. Este material pódese elaborar a partir de residuos de froitas tropicais xerados das grandes plantacións. Por iso, unha investigación exhaustiva sobre a produción de PHB a partir de residuos alimentarios sería o seguinte paso para este análise, xa que reduciría o impacto que xeran os residuos tanto no mar como na industria alimentaria, contribuíndo tamén á economía circular.

Os resultados da segunda parte conclúen que é necesario intervir no sector da pesca tanto para mellorar o proceso de obtención de recursos do mar como para diminuír os residuos que se xeran e verten ó océano. Polo tanto, as técnicas aplicadas no Capítulo 6 diminúen os impactos xerados polos barcos de pesca e o estudo e a busca de materiais biodegradables que substitúan ós convencionais diminuírá os vertidos xerados a partir das redes de pesca e dispositivos que axuden á actividade, contribuíndo a previr e diminuír a contaminación mariña por parte destes.

A terceira parte analiza aquelas actividades en torno ó mar como lugar de lecer e os residuos plásticos que derivan destas e todas as actividades anteriores. Actividades como o surf requiren da construción de materiais (táboas) que xeran un gran impacto. Como a fabricación de táboas de surf é extrapolable á fabricación de pequenos equipos mariños que utilicen os mesmos materiais, desenvólvense, aplícanse e válídanse técnicas enfocadas á economía circular co obxectivo de construír un modelo de produción de equipos mariños máis sostible. Todas estas actividades descritas anteriormente son algunhas fontes de plásticos no mar. Os plásticos no mar son un residuo importante que xera un gran impacto no océano. O último obxectivo desta parte é contribuír ó coñecemento das fontes e sumidoiros que xera un gran impacto no océano, así como as súas transformacións e as estratexias de xestión de residuos plásticos. Finalmente realízase unha análise de fluxos de forma dinámica, mediante a modelización de fluxos e stocks, e desenvólvense e aplícase un modelo multimedia que prevé o comportamento das tendencias destes compostos.

No CAPÍTULO 8 analízase o proceso tanto de fabricación como o uso de táboas de surf. Hoxe en día é posible unha revolución radical no eido produtivo grazas a políticas de loita contra a crise ambiental e o progreso tecnolóxico, como a Economía Circular. As actividades de lecer no mar son actividades antrópicas que teñen un impacto potencial, non só no medio mariño na fase de uso (por exemplo, os microplásticos) e na fase de final de vida (por exemplo, os residuos plásticos oceánicos), senón tamén na fase de fabricación, é dicir en todo o seu ciclo de vida. Esta última etapa tamén é a máis importante para previr e/ou reducir os impactos mediante por exemplo, o eco-deseño. Este capítulo ten como obxectivo analizar o sector da fabricación de equipamentos mariños utilizando polímeros reforzados con fibra (que potencialmente emiten COV co consecuente impacto toxicolóxico) desde a perspectiva da

economía circular para identificar solucións sostibles para a fase do proceso de fabricación. O caso de estudo seleccionado é un taller de equipos mariños que utiliza un polímero reforzado con fibra. Modifícase, adaptación e aplícase a este caso unha metodoloxía para identificar sistemas industriais sostibles previamente validada. A metodoloxía aplica tres ferramentas: Análise de Fluxos de Materiais e Enerxía para identificar os Fluxos Mellorables (IF) do proceso, Análise das Melloras Técnicas Dispoñibles (MTD), para propoñer as técnicas máis axeitadas que melloren eses fluxos. Por último, realízase unha Análise de Impacto (IA) para avaliar e comparar os efectos sobre os seres humanos e ecosistemas, tanto no escenario do caso de estudo como nos mellorados. Identificáronse dez fluxos mellorables para o proceso, e en consecuencia, propuxéronse quince candidatos a Melloras Técnicas Dispoñibles co obxectivo de actuar sobre estes fluxos. A aplicación destas técnicas nun sistema mellorado, permite reducir a cantidade de material e as emisións reducindo o impacto. A combinación destas ferramentas confirmouse como unha moi boa opción para a avaliación de procesos tendo en conta criterios de sustentabilidade. A avaliación de impacto permitiu comparar o escenario base que mostra unha redución dos impactos polas mellores técnicas dispoñibles seleccionadas.

No CAPÍTULO 9 contribúese ó coñecemento de fontes e sumidoiros de plástico no océano, así como as súas transformacións e estratexias de xestión. Actualmente, o 60-80% do lixo é plástico, e case o 10% acaba directamente ou indirectamente no océano. Os plásticos adoitan sufrir fotooxidación producindo microplásticos. A estes microplásticos derivados da descomposición de plásticos máis grandes chámanse microplásticos secundarios, os cales non se poden extraer simplemente dos océanos e, unha vez mesturados, entran na cadea alimentaria e poden ter efectos tóxicos. Este capítulo revisa a información actual existente sobre o tema na literatura científica. A continuación, analízanse as estratexias actuais de xestión do plástico no medio mariño, co obxectivo de identificar posibles necesidades e melloras desde un punto de vista sostible, e definir novos enfoques. Simultaneamente, realízase unha análise de fluxos de materiais en diferentes medios do medio mariño mediante dinámicas de sistema. Desenvólvese un modelo preliminar de mobilización de plásticos no océano a outros medios do medio mariño (como sedimentos e biota) e validase cos datos existentes dos pasos anteriores do capítulo. Este capítulo amplía os coñecementos actuais sobre a xestión dos plásticos, as súas transformacións e acumulación no medio mariño e os efectos nocivos sobre o mesmo. Así mesmo, implícase, executa e valida un modelo dinámico preliminar de mobilización de plásticos no océano. O modelo desenvolvido pódese usar para predicir tendencias na distribución dos plásticos no océano co tempo. Ademais, pódense observar os depósitos de plásticos máis importantes do océano. Aínda que os plásticos sofren transformacións no medio mariño, non é un medio de eliminación xa que a maioría deles non son biodegradables. A maioría dos plásticos acumúlanse no fondo do mar. A proporción de microplásticos que se atopan nos sedimentos é maior que a dos macroplásticos.

Os resultados da terceira parte conclúen que unha vez máis as destas técnicas sostibles que están baixo o enfoque do pensamento do ciclo de vida son axeitadas para contribuír a unha diminución do impacto ambiental. Ademais reafirmase a importancia da boa xestión dos plásticos en toda as actividades para que estes non rematen no mar e na cadea alimenticia.

Polo tanto para rematar, obsérvase que as ferramentas utilizadas en cada capítulo son válidas para minimizar os impactos xerados nas actividades humanas relacionadas co mar. Ademais, todos os capítulos contribúen en maior ou menor medida á economía rexenerativa. Por un lado, contribúen a diminuír os impactos xerados polo sector pesqueiro e o procesado dos seus produtos, o que axuda a utilizar os recursos extraídos do mar dunha maneira máis sostible. Por outra banda, a análise das actividades de lecer é fundamental para diminuír o impacto tanto na fabricación como no uso de material recreativo, podéndose extrapolar a calquera equipo

mariño fabricado co mesmo material. Finalmente, a análise da valorización dos residuos xerados na industria alimentaria, o coñecemento dos materiais que máis residuos provocan na pesca (redes) e a predición do movemento dos plásticos no mar, aportan información que permite anticiparnos e minimizar o problema da contaminación mariña. Polo tanto esta tese contribúe a protexer e obter un océano máis limpo e sostible.

CHAPTER 1. INTRODUCTION

1.1. THE OCEAN AND ITS NATURAL CAPITAL

From the surface to the depths, the ocean makes up the most important ecosystem on the Earth, being the largest reserve of species that inhabit the planet (MITECO, 2024a). The importance of marine ecosystems is such that approximately 61% of the world's Gross Domestic Product comes from oceans and coastal areas (UN, 2024a). Although much remains to be discovered, marine science is advancing rapidly to reveal the properties of the deep sea (biophysical, geochemical and ecological). As this understanding grows, deep sea resources will begin to be exploited more widely, representing the hopes of many for a Blue Economy (Hoagland et al, 2020). The Ocean provides us with services such as food, education, livelihoods, medicines, transportation, communications, enjoyment, treatments for diseases and is key in climate regulation (Hernández-Blanco et al, 2024). It therefore represents a reserve of natural capital vital for the life and well-being of humans (Zhang et al, 2024).

Natural capital, as shown in Figure 1.1, is the set of natural resources, both renewable and non-renewable in ecosystems, that provide us with essential services for human well-being (EC, 2024a). These natural resources offer environmental assets to human beings through regulatory, support, provisioning or cultural ecosystem services. Biodiversity plays a key role, for example in forests, a high diversity of tree species, maximizes resource use, leading to greater growth and productivity. Furthermore, it is known that a forest with many different species has greater resistance and resilience to disturbances (Luu et al, 2024). The inventory and accounting of natural capital could inform policies for the sustainable exploitation of resources and services allowing their proper management (Zhang et al, 2024). Decision making in natural resource management normally requires a cost-benefit analysis of an activity considering a balance between environmental, social and economic impacts. Cost-benefit analysis techniques tend to require these impacts to be quantified to understand the importance and acceptability of an activity (Niner et al, 2024). Natural capital accounting is a tool to measure changes in the stock of natural capital in accounting and reporting systems (EC, 2024b). In 2015, a WWF (World Wildlife Fund) report estimated that the value of traded ocean goods and services was approximately \$24 trillion. If this value is compared with that of the ten main economies in the world, the ocean would occupy seventh place worldwide, behind the United States, China, Japan, Germany, France and the United Kingdom, and ahead of Brazil, Russia and India (Hernandez-Blanco et al, 2024). Achieving an equitable Blue Economy requires reconsidering historical extractive uses of ocean natural capital in Favor of more sustainable activities (Forrest et al, 2023). Poor management of this wealth of resources causes excessive exploitation of species, pollution, climate change, loss of habitats, increased diseases and lack of awareness among other problems (OECD, 2016). Biodiversity plays a fundamental role in the ecosystem services of our natural capital. The services provided by biodiversity are essential for the proper functioning of ecosystems, such as nutrient cycling, carbon sequestration, pest regulation or pollination (FAO, 2024). In addition, it has scientific, aesthetic, educational, recreational and ethical values. Surpassing the tangible and the calculable (Milo, 2023).

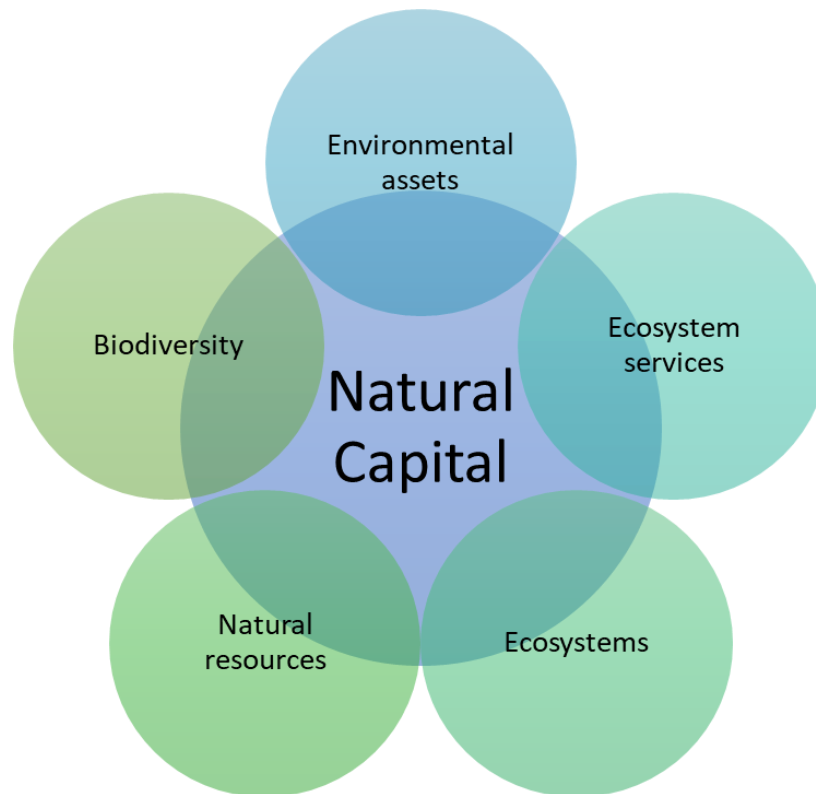


Figure 1.1. Natural Capital

1.2. INTERNATIONAL POLITICAL CONTEXT

The concept of natural capital began to gain relevance in economics and environmental management worldwide since the Brundtland Report, published in 1987 by the “World Commission on Environment and Development”. This report highlighted the importance of conserving and sustainably using natural resources and tries to reconcile economic development with the protection of social and environmental balance (EC, 2024b). Therefore, it was recognized that natural resources and ecosystem services are fundamental to human well-being and the economy, and their degradation can have negative consequences.

In 1949, the depletion of natural resources was already being discussed at the UN (United Nations) scientific conference on the “Conservation and Use of Resources in New York”. However, it was not until 1972 when true concern for environmental conservation began at the First “Earth Summit” in Stockholm. It was also at this time that the agency specialized in dealing with environmental issues, UNEP (“United Nations Environment Programme”) was created (UN, 2024b). Later, in 1987, with the publication of the aforementioned Brundtland report, a real boost was given to environmental issues and the concept of sustainable development as such was introduced for the first time. In Figure 1.2 you can see how, from this moment on, the most important conventions and meetings in relation to the environment to date are held and, in parallel, the European Community develops its particular environmental regulations. This part is important to follow and understand environmental management throughout history, along with the most important concepts to deal with.

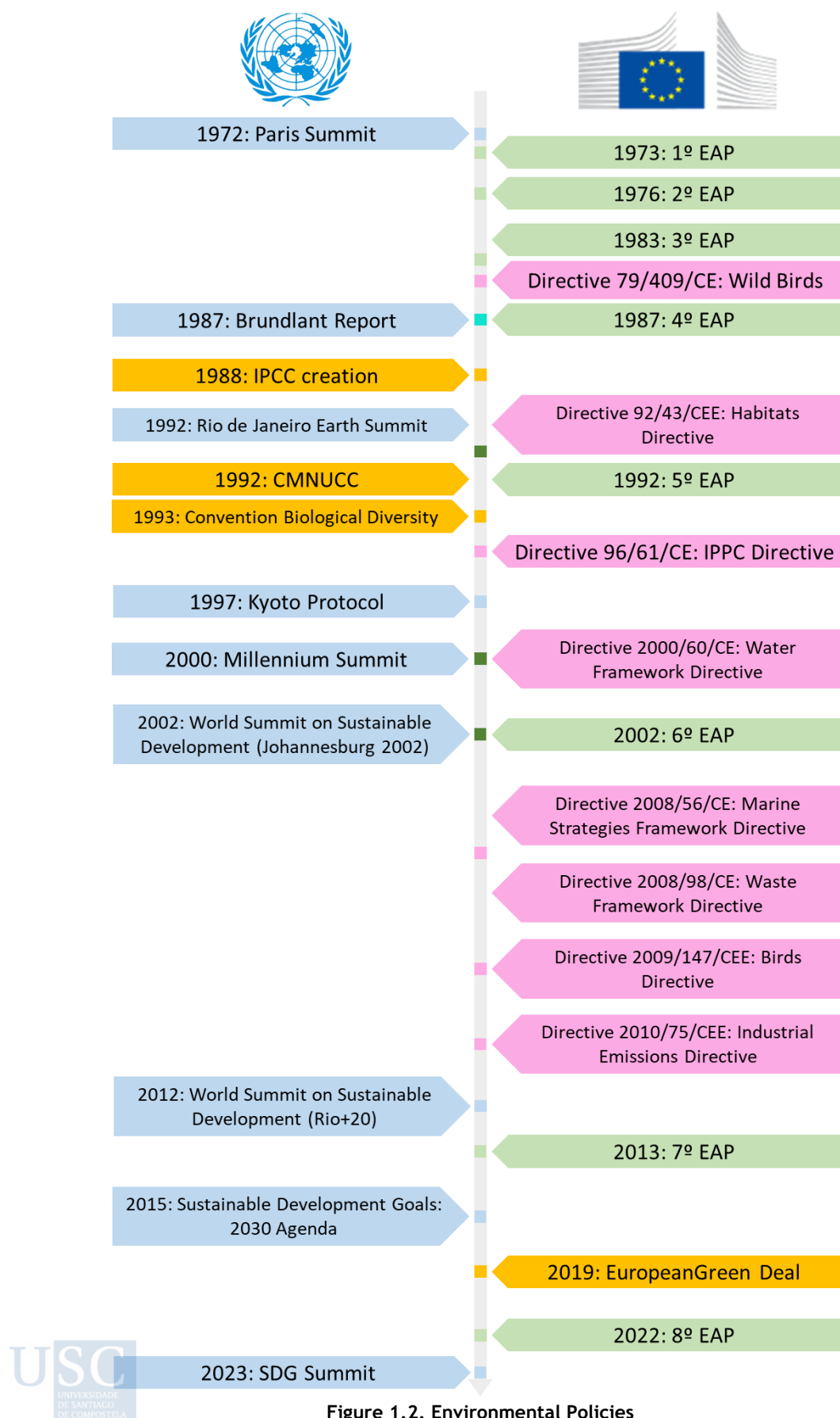


Figure 1.2. Environmental Policies

Once the environmental problem was exposed worldwide and concepts as important as sustainable development were introduced, the “Earth Summit” was held in Rio de Janeiro in 1992. Environmental issues were discussed and commitments were established to address problems such as climate change, deforestation and loss of Biodiversity (UN, 2024c). One of the main outcomes of this conference was the creation of “Agenda 21”, which dictated new strategies to invest in the future and achieve overall sustainable development in the 21st century. On the other hand, at this same conference, the signature for the “United Nations Framework Convention on Climate Change” (UNFCCC) was opened. The importance of the UNFCCC was due to the fact that it led to the most influential action on climate change that has been undertaken to date, the Kyoto Protocol (1997) (UN, 2024c). Another important result was the opening for signing of the “Convention on Biological Diversity”, whose previous work began in 1988 through the UNEP. This arises in response to the great threat of species extinction caused by human activities, taking into account that resources and diversity are fundamental for the economic and social development of humanity (CBD, 2024). Eight years later, in 2000, the Millennium Summit was held in New York. It established the eight “Millennium Development Goals” aimed at addressing poverty, education, gender equality, health and the environment by 2015. This was of great importance for the conventions that follow it (UN, 2000). Among the millennium goals, Goal 7 aimed to “Ensure environmental sustainability”. One of its targets was to “incorporate the principles of sustainable development into national policies and programs and reverse the loss of environmental resources” (MITECO, 2024b), giving importance to our natural capital. Commemorating 20 years since the “Earth Summit”, in 2012, the “United Nations Conference for Sustainable Development Rio+20” (Rio de Janeiro) was held. The objective was to “ensure renewed political commitment to sustainable development, assess progress and gaps in the implementation of agreed commitments, and address new and emerging challenges”. This Conference resulted in the agenda “The Future We Want”, which emphasized the reaffirmation of the commitment to meet the Sustainable Development Goals (SDG) or Millennium Goals by 2015 (UN, 2012). In 2015, the United Nations met again to review the objectives proposed in the previous conference and the “2030 Agenda” for Sustainable Development was created. The “2030 Agenda” is an action plan in favour of people, the planet and prosperity, which also intends to strengthen universal peace and access to justice. It was signed by 193 member states of the United Nations and sets out 17 objectives with 169 goals (MDS, 2024). These goals were reviewed in 2023 at the SDG Summit in New York. This marked the halfway point of the deadline set to achieve the “2030 Agenda” and the “Sustainable Development Goals” (UN, 2024d).

1.2.1. Sustainable Development Goal 14: Marine Life

“Sustainable Development Goal 14” (SDG 14), “Life below water,” calls for the conservation and sustainable use of marine resources. To achieve this, governance, economic development, environmental protection and international communication must align and facilitate concerted action between marine ecosystems and economic systems (Forrest et al, 2023).

Through SDG 14, we seek to address the multiple threats facing the oceans, such as pollution, acidification, overfishing and loss of biodiversity, promoting actions to protect and restore the health of marine ecosystems (UN, 2024e).

In order to achieve each SDG, the 2030 agenda provides each one with targets. Each of these targets have its indicators that are measurable on which its evolution is analysed (UN, 2015; UN, 2017).

- “By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take measures to restore them to achieve healthy and productive oceans”.
 - “Proportion of national exclusive economic zones managed using ecosystem-based approaches”.
- “By 2020, capture and stop overfishing, illegal and unregulated fishing, and destructive fishing practices. Implement scientifically based management plans to restore fish populations to the level of maximum sustainable performance determined by their biological characteristics”.
 - “Proportion of fish stocks within biologically sustainable levels”.
- “By 2020, conserve at least 10% of coastal and marine areas, in accordance with national and international law and based on the best available scientific information”
 - “Coverage of protected areas in relation to marine areas”.
- “By 2020, ban fishing subsidies that cause overcapacity and overfishing, eliminate those that promote illegal, unreported and unregulated fishing, and prevent new similar subsidies. Recognize the need for special treatment for developing countries. This approach must be central to negotiations on fisheries subsidies at the World Trade Organization”.
 - “Progress by countries in the degree of implementation of international instruments aiming to combat illegal, unreported and unregulated fishing”.
- “By 2025, prevent and significantly reduce marine pollution of all types, particularly from land-based activities, including marine litter and nutrient pollution”.
 - “Index of coastal eutrophication and floating plastic debris density”.
- “By 2030, increase the economic benefits to small island developing States and least developed countries from the sustainable use of marine resources, including through the sustainable management of fisheries, aquaculture and tourism”.
 - “Sustainable fisheries as a proportion of GDP in small island developing States, least developed countries and all countries”.
- “Increase scientific understanding, strengthen research capacity and transfer marine technology, following the guidelines of the Intergovernmental Oceanographic Commission. This seeks to improve the health of the oceans and harness marine biodiversity for the development of developing countries, especially small island states and least developed nations”.
 - “Proportion of total research budget allocated to research in the field of marine technology”.
- “Provide access for small-scale artisanal fishers to marine resources and markets”
 - “Progress by countries in the degree of application of a legal/regulatory/policy/institutional framework which recognizes and protects access rights for small-scale fisheries”.
- “Improve the conservation and sustainable use of the oceans and their resources in accordance with international law, in particular the United Nations Convention on the Law of the Sea. This convention provides the legal framework for the conservation and sustainable use of the oceans, as it is mentioned in paragraph 158 of “The future we want””.
 - “Number of countries making progress in ratifying, accepting and implementing through legal, policy and institutional frameworks, ocean-related instruments that implement international law, as reflected in the United Nations Convention

on the Law of the Sea, for the conservation and sustainable use of the oceans and their resources”.

- “Minimize and address the impacts of ocean acidification, including through increased scientific cooperation at all levels”.
 - “Average marine acidity (pH) measured at agreed suite of representative sampling stations”.

The United Nations “2030 Agenda” for Sustainable Development framework helps harmonize development with the ocean and climate agendas through the principles of the Blue Economy.

1.3. EUROPEAN POLITICAL CONTEXT

Figure 1.2 shows how, in response to the environmental commitments assumed at successive UN summits, the European Union publishes the Framework programs and develops its first environmental regulations.

The first Environmental Action Plans (EAP) forged principles such as “the polluter pays”. They also laid the pillars for the defence of environmental interests in the community and set the rational use of natural resources compatible with economic development as a major objective. Furthermore, the implementation of these meant the approval of numerous directives to approximate state legislation on matters such as water and air pollution, noise and waste, thus setting initial community standards for environmental quality (García Lupiola, 2021). It was in 1979, when the Birds Directive was forged, the oldest environmental law in the European Union. This, together with the Habitats Directive (1992) (“Nature Directives”), formed the backbone of EU biodiversity policy and are the legal basis for Natura 2000 (EC, 2015a). In the years following the 1992 Rio Earth Summit, numerous European regulations emerged in relation to climate change and industrial emissions in order to minimize them. For example, the IPPC (“Integrated Pollution Prevention and Control”) directive, published in 1996, is of great importance for this chapter. This it emerged as a legislative instrument aimed at improving sustainability and environmental protection in Europe, promoting cleaner and more sustainable industrial practices (EC, 2024c). It seeks to ensure that EU industrial facilities operate in an environmentally responsible manner, minimizing their impact on the environment and promoting long-term sustainability. Today this directive is recast together with six other directives in “Directive 2010/75/EU on Industrial Emissions” (MITECO, 2024c).

Currently, the EU is a global leader in protecting the environment and promoting sustainable development. Europe has assumed its leadership role in the implementation of the SDGs (EC, 2019a). After seven EAP and the numerous regulations that have emerged in relation to the environment in Europe, in 2022 the VIII Environment Framework Plan emerged with very ambitious objectives that included biodiversity, the reduction of pollution and the promotion of the economy circular and regenerative. In addition to seeking the integration of the environment in all policies and sectors to promote sustainability (EC, 2024d).

The Biodiversity Strategy for 2030 is a solid and forward-looking plan to safeguard nature and counteract the deterioration of ecosystems. The European Union is establishing specific initiatives and commitments such as new rules to restore biodiversity and ecosystems. The Nature Restoration Regulation aims to establish recovery measures covering at least 20% of EU land and 20% of sea areas by 2030 (EU, 2024a). These measures are of high urgency since only 15% of habitats are in good condition and 38% of fish stocks are in poor condition, and the situation is getting worse (EU, 2024b).

On the other hand, the transition towards a circular and regenerative economy is another fundamental pillar of the EU's environmental policy. This approach seeks to reduce resource

waste and encourage the reuse, recycling and regeneration of materials and products. The EU has implemented a series of measures to promote the circular economy, such as the adoption of regulations for waste management and the promotion of sustainable business models. This transition not only contributes to the protection of the environment, but also drives innovation and job creation (EC, 2024e).

1.4. SUSTAINABLE DEVELOPMENT OF ECONOMIC ACTIVITIES RELATED TO THE MARINE ENVIRONMENT

Economic activity in the oceans is increasing due to population and economic growth, climate changes, the environment and technological advances. It is because of this the excess pressure to which these ecosystems are being subjected can represent a limitation for the development of the economy (OECD, 2016). Faced with this challenge, the need arises to achieve a cleaner ocean by reducing the environmental pressures associated with the industry and develop an innovative approach that promotes economic prosperity and environmental preservation.

The current “take-make-use-dispose” economic model has been standard practice for many years. This system has led to the depletion of natural resources and widespread contamination of ecosystems, which also represents an economic problem (Usman, et al, 2024). The extensive consumption of resources requires sustainable management to limit their depletion, control environmental impacts, climate change and biodiversity loss (Stoenoiu and Jäntschi, 2024).

Given the growing concern about environmental preservation and the challenges of climate change, the new Circular Economy (CE) production model is gaining attention. This model aims to retain resources in circulation, and advocates management strategies such as reuse, recycling and product reduction, contributing to a regenerative economy (Leite Gonella et al, 2023).

This CE model, in addition to reducing habitat alteration, limiting biodiversity loss, will reduce total annual greenhouse gas emissions. Creating more efficient and sustainable products from the beginning would help reduce energy and resource consumption, as it is estimated that more than 80% of a product's environmental impact is determined during the design phase (EC, 2024e). This type of more circular and regenerative economy implies the need for a shift towards policies and practices based on sustainability (Kovacic Lukman et al., 2016).

The European Union (EU) has been a pioneer in promoting policies aimed at promoting the circular economy and environmental sustainability. Since 1973 with the first EAP, until the eighth and last EAP on the environment, the circular economy was present (EC, 2024e). In 2020, the European Commission presents the “New Action Plan for the circular economy for a cleaner and more competitive Europe”. This established a broad framework for action to accelerate the transition towards a more regenerative growth model (EC, 2024f). Taoumi et al, (2024) observes that the circular economy can be closely linked to waste management as a tool to recycle and reuse residual resources. This is because the life cycle of a process or product offers the means to quantify, manage and reduce the linked impacts of the process or product (Taoumi et al, 2024). Therefore, the circular economy involves minimizing waste, using materials from others that have reached the end of their useful life as input for the manufacturing of products. This is called industrial symbiosis (EC, 2015b, 2015c).

To promote best practices in different industrial sectors, the European Commission has the “Reference Documents on Best Available Techniques” (BREF) (EC, 2015b, 2015c). The BREF Documents began to be produced with the entry into force of Council “Directive 96/61/EC” on “Integrated Pollution Prevention and Control” (IPPC) and provided detailed technical guidance on the most advanced and efficient technologies and processes available in each sector. The

objective of these documents is to help industrial facilities reduce their environmental impact and comply with established emission standards. (MITECO, 2024d).

The BREF Documents include a compilation of “Best Available Techniques” (BAT) for each industrial sector. BAT are the most effective and advanced techniques to prevent or control pollution and are based on the application of technologies, processes and practices that have been proven to be effective in terms of reducing emissions and protecting the environment (EC, 2024g). With the adoption of the revised Industrial Emissions Directive in 2024, which modifies “Directive 2010/75/EU”, BREFs are expected to continue to play a crucial role in the regulation of industrial emissions in the EU. This directive will provide an updated framework for the prevention and control of industrial pollution (EC; 2024h).

1.4.1. Management tools

Industrial ecology studies the possible transition of industrial production systems to industrial ecosystems that can act as natural ecosystems (Clift & Druckman, 2016), and identifies the circulation of flows of matter and energy (Saavedra et al, 2018). Furthermore, it interconnects human activities and industrial production with the surrounding ecosystems, thus seeking more sustainable industrial systems (Ayres et al., 2001). Within industrial ecology, life cycle thinking plays a fundamental role.

Life cycle thinking (LCT) is a methodology that evaluates the complete cycle of a product or process, from the extraction of raw materials to final disposal, taking into account all associated environmental impacts (Farjana et al, 2021). It is used to identify the stages of the life cycle that have the greatest environmental impacts and to identify opportunities for improvement in terms of efficiency and sustainability (Curran, 2016). Tools such as Life Cycle Analysis (LCA) or Material and Energy Flow Analysis (MEFA) emerge around life cycle thinking that facilitate the process towards sustainable development (Taboada Gómez et al., 2016).

MEFA is a tool that explores the stocks and flows of materials and energy in a system (Taulo and Sebitosi, 2016; Ayres et al., 1998). Furthermore, Cristobal Andrade in 2012 demonstrated that it is a useful tool to identify Improvable Flows (IF) in a system. These are defined as quantitatively relevant flows that can be improved if managed properly, and they are selected considering their relevance over the entire system in terms of quantity (Bello Bugallo, 2012). Therefore, this approach can be used to define more sustainable systems. Flow identification tools are used to detect some specific flows whose qualitative and quantitative properties make them susceptible to improvement (Cristóbal Andrade, 2012).

On the other hand, the analysis of Best Available Techniques (BAT) is a comprehensive process used to identify and promote best environmental practices in industrial sectors (MITECO, 2024e). This tool provides a complete collection of techniques that are likely to improve processes, so they seem a good option to improve the detected IF for a given process (Bello Bugallo 2012).

By integrating these approaches and tools, a more complete and accurate understanding of industrial systems and their impact on the environment can be obtained. By considering both the qualitative and quantitative aspects of the life cycle of products and processes, as well as the best practices and technologies available to improve sustainability, concrete opportunities can be identified to move towards a more circular and sustainable economy. The combination of these tools has been validated in different sectors, from the food industry (Bello Bugallo et al, 2012), in waste management plants (Viruega Sevilla et al, 2022), in a hydrogen production plant (Cristobal Andrade et al, 2014) or even in a tile manufacturing plant (Torres Rodríguez et al, 2014).

Although these methodologies have been widely used in recent years and combined in different industrial sectors, until now they had not been validated in mobile industrial systems such as a fishing boat. Furthermore, economic activity in the ocean, as mentioned above, is constantly growing, because of this a good management of the resources it provides is important, as is protection. Therefore, the main objective of this thesis is to contribute to the identification of sustainable techniques that facilitate the path towards a regenerative economy. Through a life cycle approach, human activities related to the sea as a provider of food raw materials and as a host for enjoyment activities are analysed.

CHAPTER 2. OBJECTIVES

The main objective of this thesis is to contribute to the identification of sustainable techniques to facilitate the path towards a regenerative economy. Through a life cycle approach, human activities related to the sea as a provider of food raw materials and as a host for enjoyment activities are analysed. This will allow us to achieve a cleaner ocean from which to obtain resources in an efficient and sustainable way, protecting it by reducing the environmental pressures associated with different human activities such as fish and seafood transformation, the fishing and enjoyment. Figure 2.1 shows different processes to be analysed organized in different parts.

The specific objectives of this thesis are divided into three parts. The first part deals with fish and seafood transformation activities. The second part deals with activities related to the fishing sector. The third analyses those activities around the sea as a place of enjoyment. Material and energy analyses are carried out to identify impacts of resources and waste, and propose solutions based on the Best Available Techniques. Chapter 9 is dedicated to plastics in the sea that come from all the previous activities, the analysis of the flows is carried out dynamically, through the modelling of flows and stocks, and the development and application of a multimedia model that predicts trends behaviour of these compounds.

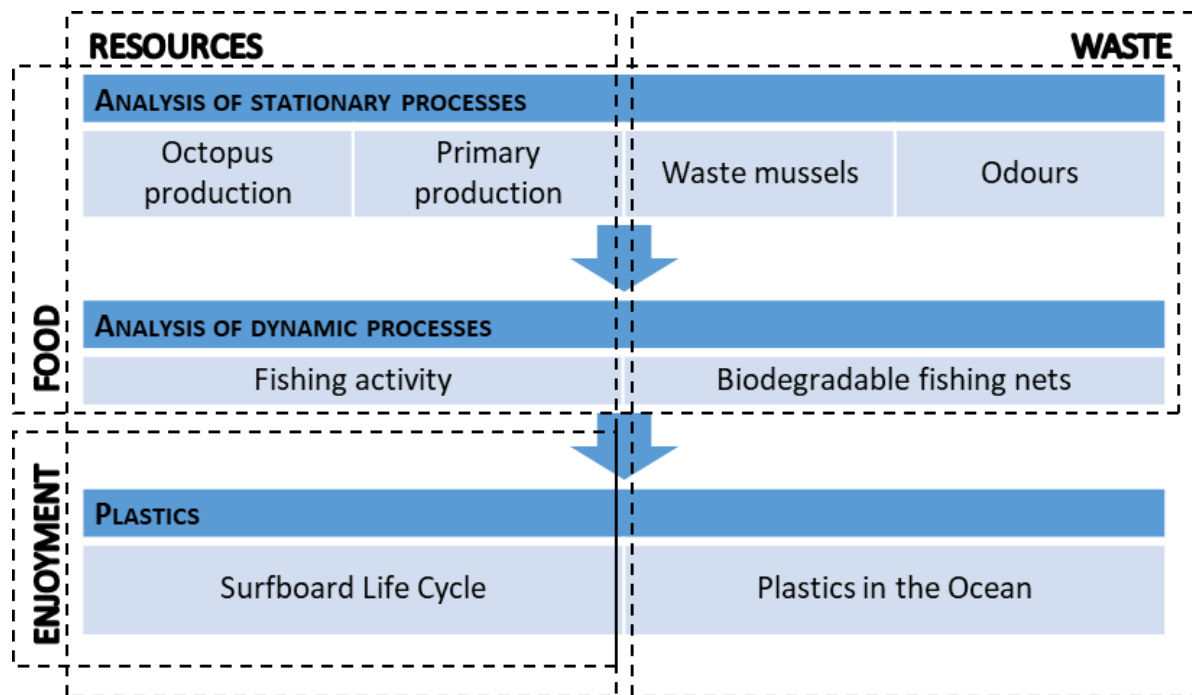


Figure 2.1. Summary of the objectives

The first part deals with fish and seafood transformation activities. Fish and seafood transformation activities are an important point in the consumption of ocean resources. Due to this and the great scope of this sector in Galicia, it is important to apply techniques that allow sustainable use of marine resources. Canning industry, and special the mussel industry, is a powerful sector in Galicia. This activity generates a great amount of waste difficult to manage,

such as mussel shells. Although there are plants that take advantage of this waste as a recovery process, odour emissions into the atmosphere become a problem. Therefore, the second objective is to identify the sources of pollution that cause this plant and search solutions and options for odorous emissions.

The second part deals with activities related to the fishing sector. The most relevant activity in the ocean is the fishing, and tuna fishing is one of the most important fisheries for its commercial value. This type of fishing generates important impacts on the environment. Due to of this and for its great socioeconomic impact in Galicia, fishing is analysed under the scope of industrial ecology. More sustainable configurations for a tuna purse seiner vessel are identified. Fishing activity is a sector of great importance in the world that generates a great amount of waste into the sea. In addition, there are fisheries, such as purse seiner tuna, that use fishing devices called FADs (Fishing Aggregating Devices) to group fishes. FADs are usually abandoned at sea and normally are made with no-biodegradable materials. For this reason, to contribute to the knowledge about these devices, to the materials used for it made, and search another material to be used as FAD a systematic review in the bibliography is carried out. This helps us to search for a biodegradable material that meets the necessary characteristics to be used as FAD or even as fishing nets. This way we will avoid the abandonment of non-biodegradable waste in the ocean.

The third part analyses those activities around the sea as a place of enjoyment and the plastics waste that come from all the previous activities. Activities such as surfing require the construction of materials (boards) that generate a great impact. As the manufacturing of surfboards can be extrapolated to the manufacturing of small marine equipment that uses the same materials, techniques focused on the circular economy are developed, applied and validated with the objective of building a more sustainable marine equipment production model.

All of these activities described above are some sources of plastics in the sea. Plastics in the sea are an important waste that generates a great impact on the ocean. The last objective of this part is to contribute to the knowledge of the sources and sinks that generate a great impact on the ocean, as well as their transformations and plastic waste management strategies. Finally, an analysis of the flows is carried out dynamically, through the modelling of flows and stocks, and the development and application of a multimedia model that predicts trends behaviour of these compounds.

CHAPTER 3. METHODOLOGY

For achieving the objectives described in the previous section, the Doctoral Thesis is developed in three parts and different chapters. Each chapter is developed independently, including, introduction, objectives, methodology, development, discussion of results and conclusions. The general process is shown in Figure 3.1.

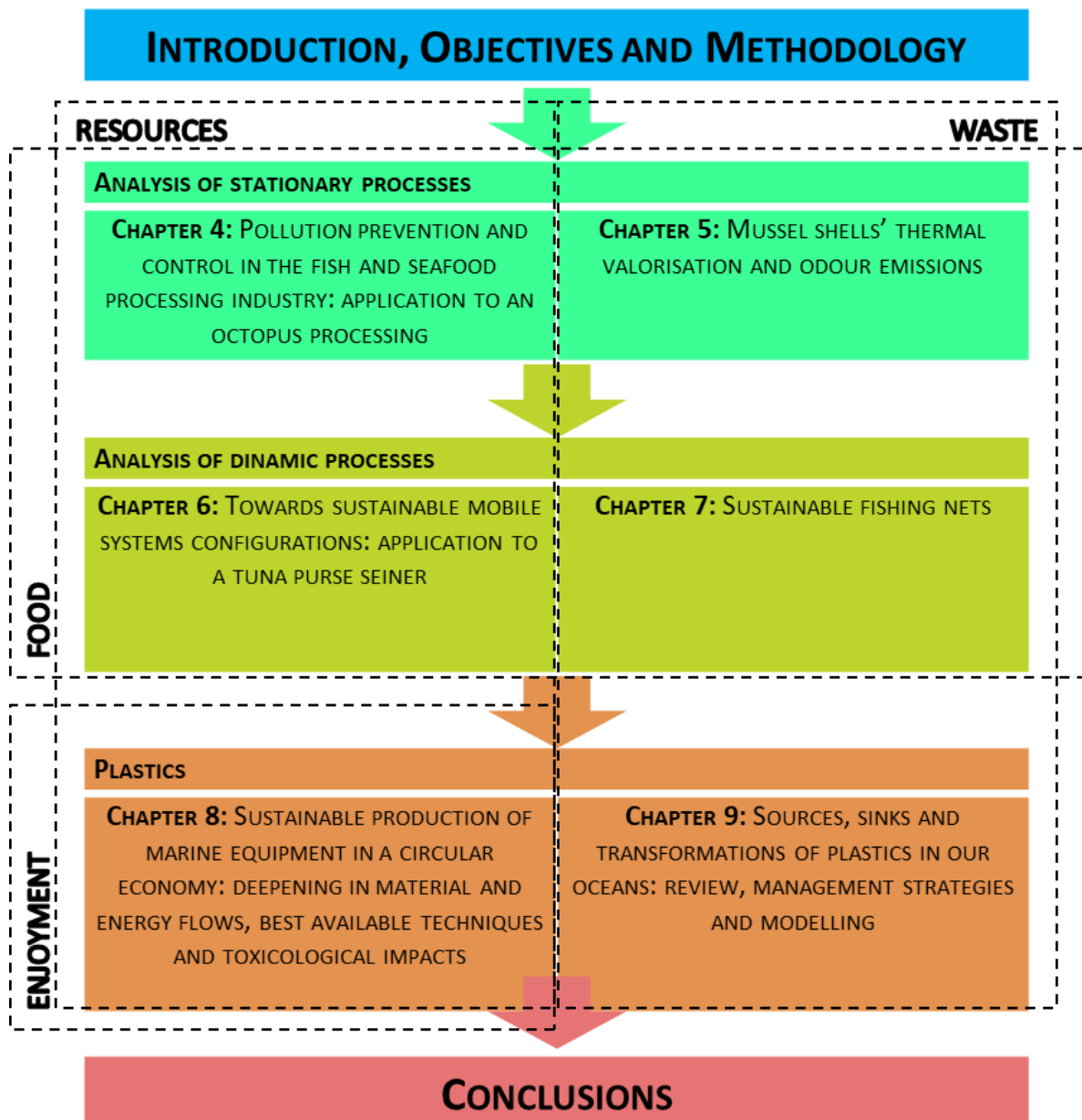


Figure 3.1. Summary of the steps followed for the development

To achieve the objectives described in the previous chapter, the Doctoral Thesis is developed in three parts and in different chapters.

The first part is made up of two chapters that deals with fish and seafood transformation activities. In the CHAPTER 4, some of the tools developed and known under the philosophy of Life Cycle Thinking (LCT): MEFA analysis and BAT (Best Available Techniques) analysis is applied. MEFA provide qualitative and quantitative information on the Improvable Flows (IF) of the system from an environmental and economic point of view and the BAT analysis applies the BAT, to reduce the IF. In this case, this methodology allows the octopus transformation activity to determine which processes and points are less sustainable and improve them from a circular economy point of view. This methodology can be applied to any sector of the fish and seafood activity, as well as the case of mussel canning. The most important problem in this sector is the high amount of mussel shell waste that is produced. To deal this problem CHAPTER 5 analyse the biggest problem in this sector: the valorisation of mussel shells. To addressed this chapter, first the results of the greening process carried out previously have been analysed. Then a qualitative and quantitative analysis is carried out to obtain improvable flows of the plant. Finally, technical solutions are proposed aimed at avoiding and reducing emissions.

The second part is made up of two chapters that deals with the fishing sector. CHAPTER 6 analyses marine fishing activity from the point of view of the LCT life cycle (from port to port). It is analysed from both a qualitative and quantitative point of view. Material and energy flows will be analysed using MEFA analysis tools. This analysis, as in CHAPTER 4, allows identifying IF in the system from a sustainable point of view using tools based on pollution prevention, a control approach and foresight of the circular economy, in this case through BAT analysis. From this analysis, the problem of non-biodegradable fishing nets and the emission of plastics into the ocean. CHAPTER 7 makes a systematic review of the state of the art, recognizes its weaknesses and compiles the studies and works that exist to date. The situation of the study system is checked and a bibliographic search is carried out using the Spanish Foundation for Science and Technology (FECYT) as a resource.

The third part is made up of two chapters that analyse those activities around the sea as a place of enjoyment and the plastics waste that come from all the previous activities. On the one side in CHAPTER 8, the construction of the surfboards is analysed to build a more sustainable production model in a marine equipment plant. To achieve this goal, three sustainable techniques are used: materials and energy flow analysis (MEFA), best available techniques analysis (BAT) and toxicological impact assessment (IA) on humans and ecosystems. The intention is to look for an improved process configuration and compare it with the conventional one. On the other side, in CHAPTER 9, a methodology that analyses the problem of plastics in the sea is applied. Both its sources and sinks, the transformation of plastics and microplastics and the need for management strategies are analysed. In addition, an analysis of the flows is carried out dynamically, through the modelling of flows and stocks, and the development and application of a multimedia model that predicts trends behaviour of these compounds.

Finally, a chapter of conclusions is made (CHAPTER 10), where the main conclusions obtained are presented.

CHAPTER 4. POLLUTION PREVENTION AND CONTROL IN THE FISH AND SEAFOOD PROCESSING INDUSTRY: APPLICATION TO AN OCTOPUS PROCESSING ACTIVITY

SUMMARY

The capture of this species, appreciated for its great culinary value, is of great importance, not only in Galicia, but in the rest of the world to which a large quantity is exported. Octopus fishing has a great impact on the ocean, but we must also add the impact of its subsequent transformation in plants like the one chosen. Due to this importance, the need arises to deal the study of the environmental aspects of this activity in order to establish strategies that minimize environmental impacts. The objective of this chapter is to apply the tools developed and known under the philosophy of Life Cycle Thinking: to the Analysis of Materials and Energy Flows (MEFA) and to the analysis of Best Available Techniques (BAT) the calculation of the carbon footprint generated of the company adds it. The calculation of the carbon footprint will indicate the CO₂ equivalent per flow, thus completing the MEFA in the identification of flows susceptible to improvement. The purpose of this chapter is to address and understand the use of these techniques in a simple way to combine them with others and seek other more complex results in the following chapters, to reduce the Environmental Impacts generated. To apply the tools, the first step is the identification of the case study. The plant is analysed in a very exhaustive qualitative way. The different operations and processes are identified, the materials that enter and the waste that leaves, in addition to the flows that exist throughout the process.

As a result, it is obtained that the flows of diesel, electricity and water are very important within the processing. To reduce these flows, forty-two best techniques are observed in the BREFs, of which twelve are already implemented. Although this percentage is not too high, it is expected that the company has increased the number of techniques implemented. On the other hand, the application of this methodology provides effective solutions to the transformation of octopus, making it a more sustainable process.

4.1. INTRODUCTION

Fishing in Galicia is an ancient activity, carried out since time immemorial. With 1498 km of coastline (Miteco, 2023), Galicia is the region of Spain with the highest fishing activity. According to the white book on fishing, the Galician fleet is made up of 48.3% of Spanish vessels, with more than 5000 registered vessels (Pesca de Galicia, 2023). Of all the fisheries, octopus fishing is of great importance because Spain is the main market for this product in the European Union (IP, 2021). This mollusc extracted by artisanal fishing and is one of the most important fleets in Galicia (Xunta de Galicia, 2007; Pita et al, 2016), with 31% of vessels licensed for it (Pesca de Galicia, 2023). Although octopus fishing in Galicia constitutes the fourth species with the highest income in the Galician fleet (Pesca de Galicia, 2023), Spain is one of the main import markets for octopus (FAO, 2022), its main importers are Morocco and Mauritania (Europa azul, 2020). This is due to its culinary importance in the area.

Galicia is the European region whose employment depends more directly on the fishing sector, with more than 40% of the fishing activity. In addition, it has promoted a large industrial activity around it (Fernandez Macho et al 2006; IGE 2023; MAPA 2023), from inshore artisanal fishing to the canning industry (Doldán et al, 2011). The sea and its industry are the fourth most important economic activity in Galicia (IP, 2022), showing significant economic income. The Galician fishing industry employed in 2020 more than 6% of the population dedicated to the industry in Galicia (IGE 2023; MAPA 2023). The Spanish processing industry is, without a doubt, the most important production scale in the Spanish fishing sector as a whole. Its current dimension figures its production in the order of 900000 tons per year, 3% being for the processing, freezing and canning of octopus (MAPA, 2007).

The fish and shellfish canning industry constitutes a fundamental sector for the economy of Galicia (NW Spain). These companies represent more than 50% of the total number of facilities in this sector in Spain, and account for 80% of national production (Bello bugallo et al, 2013). In the search to improve industrial processes, companies focus on improving technical and economic factors in order to reduce costs and increase benefits (Torres Rodríguez et al, 2011). As a consequence of this fact, the environment is profoundly affected, efficient resource management and a global reduction in the generation of pollutants associated with different production processes are necessary (Barros et al, 2009a). Pollution management involves regulatory and economic instruments and voluntary agreements between industry and public authorities (Chittock, et al, 2011). Regulations play a critical role in requiring companies to understand the connections between operational and environmental efficiencies, so they need to be adjusted over time to reflect updated understanding or new circumstances (Bello Bugallo et al, 2013). Therefore, to protect human health and the environment, public authorities are implementing different types of environmental regulations to prevent and control industrial emissions (Huybrechts et al, 2018). In the European Union with Directive 2010/75/EU (EC, 2010), standards are established to avoid or reduce waste and emissions both to the atmosphere and to water and soil, in numerous industrial activities listed in its Annex I (EC, 2010). This directive ensures the control of the impacts through the Best Available Techniques (BAT), described by the European Commission in the reference documents (BREF). BATs are described in this directive as the most efficient available techniques used to avoid or, when that is not possible, reduce emissions and the impact on the environment (Directive 2010/75/EU). These are used as a tool to minimize the Improvable Flows of a system (IF) (Taboada et al 2016), allowing for example Zapelloni et al (2019) to locate candidate BAT techniques to improve the surfboard manufacturing process. Other researchers have used BATs to improve different plants, such as Telenga-Kopyczyńska et al (2021), in Polish coke plants or Simsek-Yunus et al (2022) in the textile industry. These IF are located through one of the tools provided

by the Life Cycle Thinking (LCT) philosophy, the Materials and Flow Analysis (MEFA) that arises from industrial metabolism (Torres Rodríguez et al, 2011).

Due to the importance in Galicia of the fishing sector and the transformation of its products, being the octopus one of the most important species. The need arises to address the study of the environmental aspects of this industry in order to establish strategies to minimize the environmental impacts. The objective of this chapter is to apply one of the tools developed and known under the LCT philosophy: MEFA analysis and BAT analysis. The first, the MEFA analysis, provides both qualitative and quantitative information on the FI of the system, from the environmental and economic point of view. The second, BAT analysis, uses technology to prevent and reduce IF by applying the Best Available Techniques, defined by economic, environmental and social criteria in the BREFs (Best available techniques Reference document). Furthermore, in order to complete the MEFA, the calculation of the carbon footprint that applies to this plant is added. This helps us better define which are the most important IFs of the plant.

4.2. METHODOLOGY

A methodology developed and validated by Torres Rodríguez et al (2011) is applied, adding to the calculation of the carbon footprint. The methodology applies an MEFA to an industrial system accompanied by the calculation of the footprint to identify its FI; and BAT analysis to select the most appropriate candidate techniques to improve the process based on the identified IF. The Figure 4.1 shows the methodology used in this chapter.

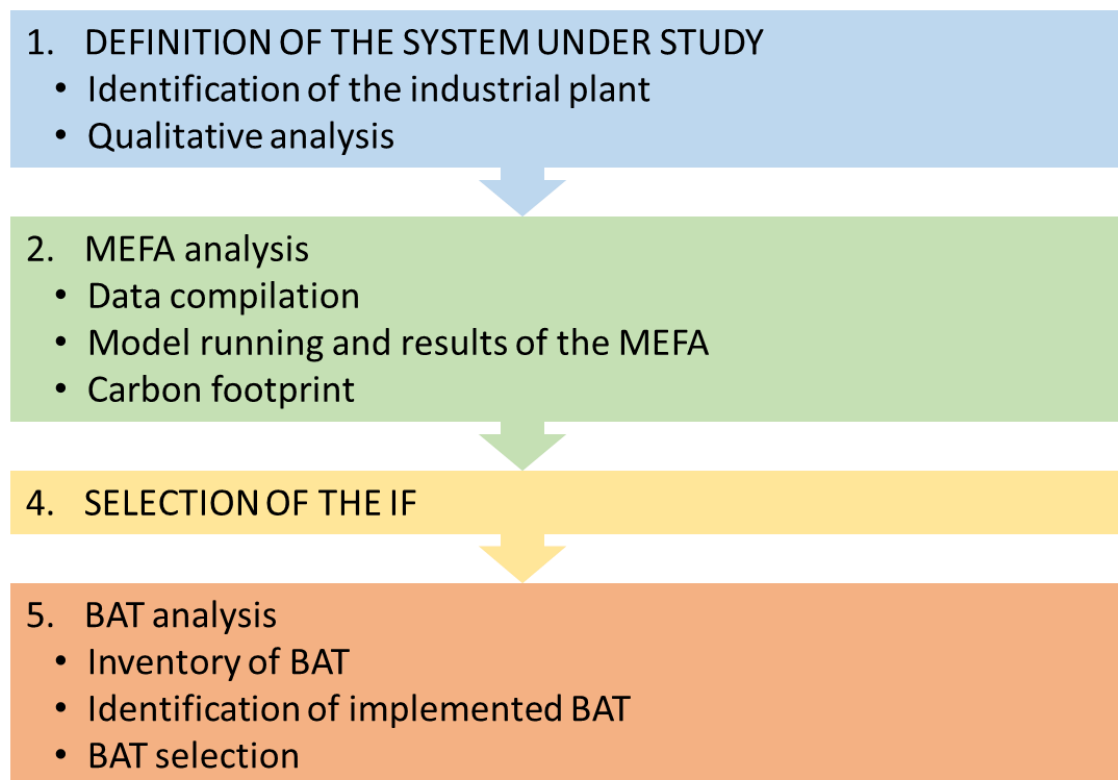


Figure 4.1. Methodology

4.3. APPLICATION OF THE METHODOLOGY TO THE CASE STUDY

4.3.1. Definition of the system under study

4.3.1.1. Identification of the industrial plant

An octopus processing plant located in Galicia (NW Spain) is the case study of this chapter. It is a small plant that identifies itself as an SME (Small and Medium Enterprise) with basic technology and that passes the appropriate health controls that allow it to produce high quality octopus. The final transformed product can be used by other food industries or directly to the final consumer. The plant carries out several processes obtaining different final products that are shown in Table 4.1.

Table 4.1. Type of products

	RAW	COOKED
Kind of product	Block	Slides in bag (Frozen)
	Tray	Whole cooked
	Bags	Tentacles
	Flower shaped	Carpaccio
	Tentacles	

Production may vary and is planned daily based on customer demand for each product. Raw materials are received trucks of 20 or 25 ton. This entry varies according to demand from 2 trucks per month to 2 per week, being able to customize the order in terms of the quantity and size of the product.

4.3.1.2. Qualitative analysis of the selected industrial process

The processing of the octopus in this factory has been divided into 4 main stages following the model proposed by Casares et al (2005) for the canning of seafood and fish. The process goes from the arrival of the reception of the raw material, until the packaged product comes out directly for sale. In the diagram of the Figure 4.2. you can see the different stages:

- **Preliminary operations:** these operations represented in blue, consist of preparing the raw material for later use. They range from the reception of both the packaging materials and the raw material to its cleaning.
- **Processing:** This is represented in green, consists of raw material handling operations to obtain the different products. Includes all operations prior to packaging.
- **Final operations:** These are represented in pink and include all the final operations once the different products have been prepared. Starting in the packaging and ending in delivery for sale.
- **Auxiliary operations:** These operations shown in purple are those operations that are not directly related to the manufacturing process, but that indirectly follow it. These are the generation of steam, necessary for cooking, or the generation of compressed air, both for packaging and for the operation of some equipment. As auxiliary operations, the cleaning and cooking of the factory workers are considered.

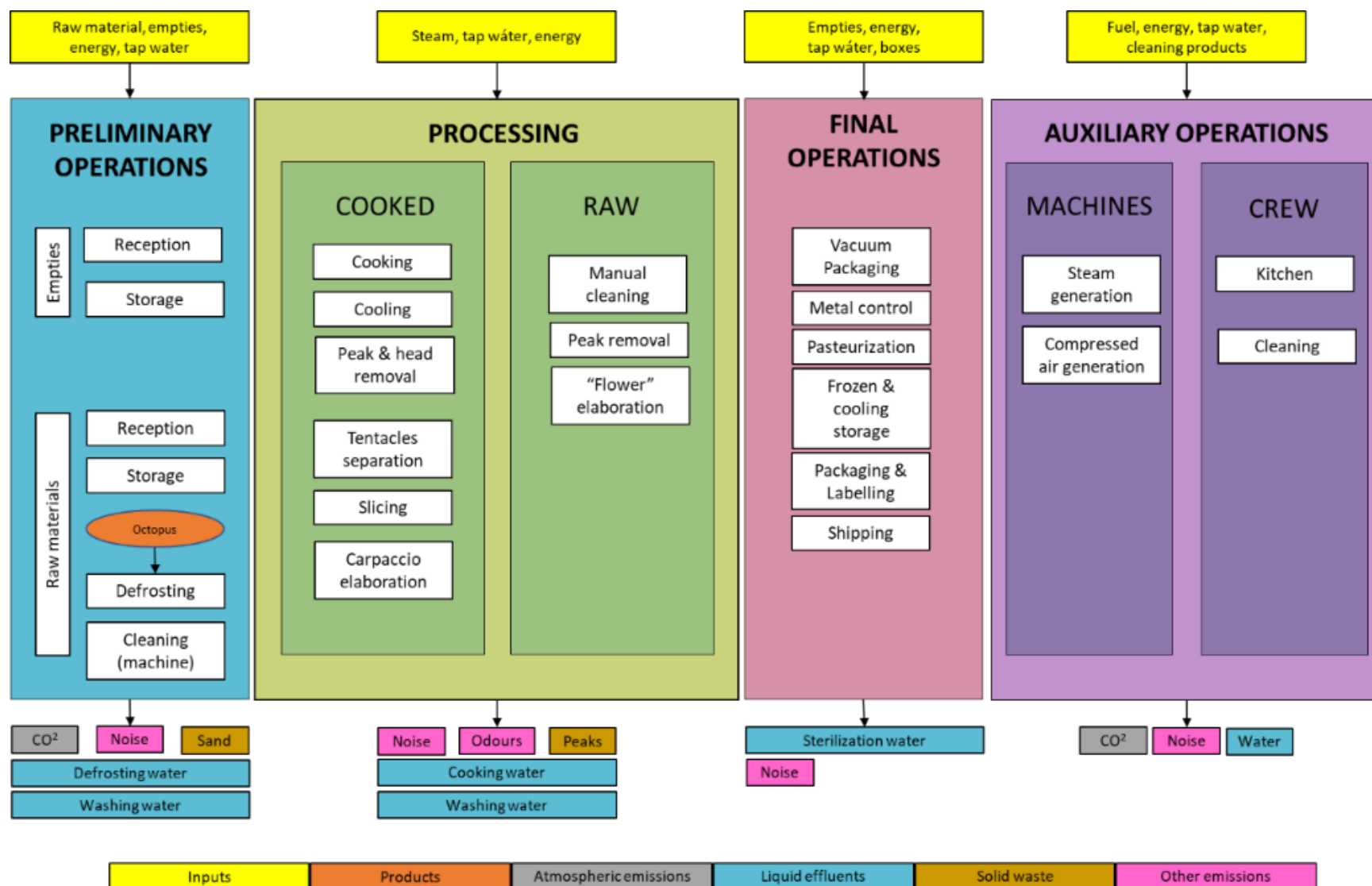


Figure 4.2. Diagram of Octopus plant

All these operations need inputs represented in yellow and outputs represented each type in a different colour as shown in the Figure 4.2.

This octopus processing plant prepares different products for sale, although some processes are common and share the same lines as can be seen in the Figure 4.3. The Figure 4.3 follows the same colour code as the Figure 4.2. The Figure 4.3 shows the diagram of the process about the transformation of octopus in this plant. It begins with the input of the raw material, which is stored in a freezing chamber until the start of production. Then, start the process although there is the possibility of marketing frozen octopus in unprocessed blocks.

The first stage of the process is the thawing of the raw material followed by an automatic preliminary washing to remove foreign bodies and marine sediments. Later, octopus can be used for two different types of products: raw and cooked.

The cooked products follow the line on the left in the Figure 4.3. This line goes through a steam cooking process in which fuel and water are mainly consumed, generating a lot of noise and residual water. Then octopus is passed through a cooling process to be able to manipulate it manually and remove its beak. From this stage comes the first cooked product, the whole octopus that can be packed in vacuum bags. The next stage in the cooking line would be the removal of the head and the separation of the tentacles. With the tentacles already separated, they prepare them whole that can be packed in a vacuum tray. Another product that is made with the tentacles would be the carpaccio, in which the tentacles are compressed in a special container for sausages. Finally, the tentacles can also go through the cutting process, making slices to pack them in vacuum trays and store them cold or jump to the frozen line, obtaining a pasteurized and refrigerated or frozen slice. All cooked products except slices, which are also frozen, pass metal screening, they are pasteurized and stored cold until they are labelled and shipped.

Frozen products go through a manual washing and peak removal stage before being processed. On the one hand, the flowering octopus is produced (a special way of marketing the whole octopus) or the octopus follows the process to produce frozen whole octopus. These products that will go through the freezing tunnel are first vacuum packed in addition to passing metal control. Once frozen, they are stored in the freezing chamber until they are labelled and shipped.



Figure 4.3. Octopus processing

4.3.2. MEFA analysis

4.3.2.1. Data recompilation

The data provided for the modelling have been acquired through visits and interviews with the personnel of the chosen case study. The data correspond to the month of June 2015, since it is the month of maximum production of the factory. The data is categorized by electricity, water and diesel bills. The most important data is the input of raw material, in this case octopus, which corresponds to 30.5 tons of total octopus for that specific month. This data corresponds to the total amount of octopus among all the elaborations. The Table 4.2 shows the quantity of octopus for each product. It's can see the quantity of octopus that enters and that leaves, with a decrease

in some cases of up to 15%. Because of this, the quantity of octopus entering is greater than the quantity leaving.

Table 4.2. The amount of octopus

	Kind of products	Kilos IN	Kilos OUT
RAW	Bag	12,412.00	13,828.00
	Block	380.00	380.00
	Flower	2,001.00	1,700.85
COOKED	Tentacle	26,253.00	11,813.85
	Whole cooked	4,315.00	1,726.00
	Slice in bag (frozen)	4,161.00	2,288.55
	Slice on Tray	2,584.00	1,421.20

The Table 4.3 also shows the consumption of the factory in the month of study, both for water, energy and diesel necessary for cooking the octopus.

Table 4.3. Factory consumption

Item	Consumption in a month
Energy in a month	22,152.00 kWh
Water in a month	465.33 m ³
Diesel oil C in a month	4,000.00 L

4.3.2.2. Model running and results of MEFA

All calculations are estimates based on data from June 2015, selected as the “standard” month in terms of production and referring to tons of final product. The units of the different consumption are difficult to unify, making it difficult to determine the consumption per ton of product. For example, to meet customer demand, some batches of products are quite specific, the consumption of machines depends on the size of the batch and the time needed to produce it. Regarding electrical energy, we do not have the consumption of all the machines that make up the factory, but we do have the most important ones. Therefore, of the 22,152 kWh consumed in a month, we observe that the most important consumption is that of cold rooms, with almost 50% of the consumption. As for the “other” item, it refers to small motors and electrical devices found in the factory, as well as the consumption of compressors and the energy expenditure produced by the office. The Table 4.4 shows the consumption of the different machines with the most costs in the factory per ton produced.

Table 4.4. Energy consumption per ton produced

Item	Consumption in a month
Cold equipment	307.50 kWh/ton
Factory lighting	89.00 kWh/ton
Vacuum equipment	13.00 kWh/ton
Shrink wrap	7.00 kwh/ton
Metal detector	5.38 kWh/ton
Washing equipment Energy	4.50 kWh/ton
Others	241.50 kWh/ton

On the other hand, water consumption is mainly used for cooking and washing the product, although it is also used for factory cleaning or staff hygiene. As for diesel, it is only used for cooking the product. Table 4.5 shows the different consumption of water and diesel per ton of product.

Table 4.5. Consumptions of water and Diesel per Ton produced

Item	Consumption in a month
Diesel in the cooking	230.00 L diesel/ ton
Water by hand washing	11.06 m ³ /ton
Water by washing equipment	4.80 m ³ /ton
Water by cooked	2.81 m ³ /ton

4.3.2.3. Carbon footprint calculation

The calculation of the carbon footprint of an organization is constituted as a tool with a double purpose: to reduce the costs involved in energy consumption for lighting, air conditioning, heating and transportation and, on the other hand, to contribute to the reduction of emissions of GHG (Greenhouse Gas) and greater environmental awareness (MITECO, 2023). To calculate the carbon footprint of the plant, data on electricity, Diesel C and water consumption, as well as the quantity of octopus that enters the factory, are used. In addition to the consumption and the input of octopus, the emission factors of these inputs are necessary to calculate the carbon footprint. The Table 4.6 shows the emission factors necessary to calculate the carbon footprint.

Table 4.6. Emission Factors

ITEM	Emission Factor	SOURCE
Octopus	5.400 kg CO ₂ eq/kg octopus	Almeida et al 2022
Electricity	0.350 kg CO ₂ eq/kWh	MITECO, 2023
Water	0.176 kg CO ₂ eq/m ³	Marin Galvin, 2020
Diesel	2.721 kg CO ₂ eq/litter	MITECO, 2023b

Looking at the emission factors you already get an overview of the input that will generate a higher carbon footprint. Taking into account these emission factors and the quantities of each of the inputs, a carbon footprint of 2,350 tons of CO₂ eq is obtained in the factory for this specific month. Table 4.7 shows the carbon footprint calculated for each entrance to the factory.

Table 4.7. Carbon footprint

ITEM	Carbon footprint
Octopus	2331.320 Ton CO ₂ eq
Electricity	7.753 Ton CO ₂ eq
Water	81.000 kg CO ₂ eq
Diesel	10.880 Ton CO ₂ eq

4.3.3. Selection of the IF

The IF can be defined as those flows of a process that, due to one or more of their specific properties, are likely to improve. The IF selected are those that had a high impact on the production process. Looking at the carbon footprint of the different entries, the big impact refers to the octopus. This is mainly due to the great impact that octopus fishing has. This carbon footprint can be decreased or increased depending on its origin. If the carbon footprint brought by the octopus itself is not taken into account, Diesel is the second improvable flow of the octopus's factory, with 10.88 tons of CO₂ eq. Diesel is used in the cooking process, so it is the

second flow that can be improved in the factory. Electricity is the next most impactful flow of the factory. When looking at the different electrical processes in the factory, the improvable flows are the electrical energy consumed by the cold equipment, the factory lighting and the vacuum packaging machine. The Table 4.8 shows the IFs selected.

Table 4.8. IF

IF inputs	Stage
Diesel	Cooking
Electricity	Cooling
Electricity	Factory lighting
Water	Washing

4.3.4. BAT analysis

4.3.4.1. Recompilation of techniques candidates to be BAT

Using the Reference documents under the IPPC Directive a total of forty-two BAT are selected to be candidates for this case study. These forty-two BATs, according to the company process, are identified those that are already implemented and those which could be implemented.

4.3.4.2. Identification of the already implemented BAT

Of the forty-two candidate techniques, twelve are already implemented in the factory, therefore, there are a total of thirty candidate BAT techniques. The Table 4.9 shows the BAT that are already implemented.

Table 4.9. BAT Implemented

Stage	Sub - stage	Implemented BAT
Preliminary operations	Reception	Switch off the engine and refrigerator unit of vehicles while loading/unloading and when parked
	Frozen storage	Automation of cold distribution and generation system
		Minimize storage times for perishable materials
	Sizing	Sorting of the raw material by size
Processing	Cooking and cooling	Control of cooking parameters. Installation of thermostat
		Cooking in fresh water
		Emptying of ovens
Final operations	Sterilization	Full - load autoclave usage
Auxiliary operations	Cleaning of facilities	Remove raw material residues as soon as possible and clean storage areas frequently
		Select and use cleaning and disinfestation agents which cause minimum harm to the environment and provide effective hygiene control
		High pressure cleaning
	Steam generation	Insulation of steam distribution system

4.3.4.3. BAT selection according to IF

The Table 4.10 collect the BAT's that could be implemented in order to improve the main aspects of the process that consumes water, diesel and electrical energy.

Table 4.10. BAT selected

Stage	Sub - stage	BATs
General		Use of by - products, co - products and residues as animal feed
		Minimise heating and cooling times
		Environmental management system
		Energy efficiency plan
		process control system (lights out)
		Low consumption lighting
Preliminary operations	Reception	Receive materials in bulk
	Frozen storage	Optimization of condensation and evaporation temperature of cooling systems
	Washing	Washers with water recirculation
		Optimization of water flow
		Cleaning of entrails and meat without mixing them
Processing	Cooking and cooling	Process monitoring
		Isolation of ovens
		Steam/vacuum cooking
		Recuperation and reusing of protein content from cooking effluent
		Cooling inside the oven by water and vacuum
Final operations	Pasteurization	Insulation of sterilization system
		Recuperation and reusing of refrigeration water from sterilization stage
		Water spray autoclave usage
	Boxing/packaging	Optimisation of packaging design to reduce the quantity
		Collect packaging material separately
Auxiliary operations	Cleaning of facilities	Dry cleaning of equipment and installations
		Minimise the use of water, energy and detergents
		Recovery of refrigeration water of autoclaves
	Steam generation	Using biogas as a fuel
		Combustion regulation and control
		Using natural gas
	Compressed air generation	Reduction of air leaks and optimisation of pressure settings
	Cooking trolleys cleaning	Washer with water recirculation
		High pressure cleaning

4.4. RESULTS AND DISCUSSION

This chapter applies different sustainable tools under the life cycle thinking approach, with the objective of preventing and controlling contamination in an octopus processing plant. The application of the proposed methodology has made it possible to identify their IFs, in this way several BATs have been proposed to reduce the IFs. Although the improvable flows are deduced from the qualitative analysis of the factory observing its most representative consumption, the calculation of the carbon footprint of the plant is also carried out. The carbon footprint shows the impact that different inputs to the process have observe a very important IF at the Octopus Input, this is due to the great impact that fishing brings. According to Almeida et al, 2022, industrial octopus fishing, which comes mainly from Mauritania, has a large carbon

footprint compared to octopus that comes from artisanal fishing. Although an average has been made between both carbon footprints, this could be much higher, since according to Blue Europe, 2020, most of the octopus consumed comes from Morocco and Mauritania. Therefore, the decrease in this IF would correspond to a change in suppliers that import their octopus from nearby artisanal fishing or a higher percentage. On the other hand, electricity, water and diesel consumption cause three IFs to which the selection of BAT selected from the References Documents can be applied. For these flows, forty-two BAT are selected, and the degree of implementation is 28%.

This chapter is based on data from the factory in 2015. Although we do not have current data from it, it is expected that the degree of implementation has increased.

4.5. CONCLUSIONS

This chapter applies a methodology that combines different sustainable tools under the life cycle thinking approach. It combines several tools to analyse an octopus processing plant and proposes techniques that can improve the process from a sustainability point of view. It is a simple system that combines MEFA, applying the calculation of the carbon footprint to identify the IFs. Finally, a BAT analysis is applied to identify candidate techniques to improve the most important flows. The objective of this combination of tools is to achieve a more sustainable configuration. The results observed for this combination of tools was a plant with a not very high degree of BAT implementation, with twelve techniques already implemented and twenty-nine possible that could be implemented. It is expected that although the degree of implementation is not very high, that currently the degree of implementation has increased.

These techniques not only help improve flows and contribute to a more sustainable process. They also contribute to a more profitable process by reducing the consumption of electrical resources, water and diesel used in the process. Therefore, the application of this methodology provides effective solutions to the octopus processing to make it more sustainable and profitable. Thus, achieving a sustainable configuration, helping the company on an economic, environmental and social level.

The application of the technologies identified in the BREF as BAT therefore contributes to preventing and reducing environmental pollution. Therefore, the application of this methodology turns out to be a good tool to locate possible critical points that can be improved and obtain a sustainable process.

CHAPTER 5. MUSSEL SHELLS' THERMAL VALORISATION AND ODOUR EMISSIONS

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

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- Authors: Bello Bugallo, P.M.; García Rellán, A.; Barros Frieiro, C.; Cristóbal Andrade L.
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SUMMARY

Seafood processing industries in the NW coast of Spain generate significant amounts of shell waste. Recent regulations and strategies on waste open up new opportunities to sustainable development through the management and the treatment of aquaculture materials, previously considered as waste. They encourage the recovery of waste and their use as raw materials in such a way that the consumption of resources is reduced and the sources of pollution can be minimised. This paper presents a plant dealing with mussel shell waste as input in its valorisation process, which is considered a priori an eco-friendly solution to the disposal of these products. It is a clear procedure to turn waste into a high value-added product like lime, a secondary but sustainable raw material with a market potential to be used in different applications. However, as a result of the thermal treatment of the shell waste, odour emissions to the atmosphere become a serious problem. The pollution caused by these odours produces an environmental and social conflict between the industry and the population of the surrounding area. Accordingly, our work aims at identifying the sources of pollution to seek solutions for the odorous emissions from the installation.

5.1. INTRODUCTION

In 2015, Spanish aquaculture generated 293,000 tons of marine products, including 277,000 tons from the cultivation of marine species (94.5% of the total production), and the rest from continental aquaculture (5.5% of the total production). The highest production of Spanish aquaculture corresponds to mussel farming (mainly *Mytilus galloprovincialis*), which in 2015 represented 77% of the total national production with 225,000 tons (FAO, 2017).

Spanish aquaculture stands out in Europe and worldwide for the breeding of bivalve molluscs. In 2015, the production of molluscs in the world was 16,473,112 of tons, which 3.8% corresponded to the European Union (APROMAR, 2017). Galicia, in the north-western coast of Spain, is the world leader in the cultivation of mussels for human consumption, producing more than 212,000 tons in 2010 (Bello Bugallo et al. 2012).

Mussels farmed in floating nurseries are hence the most important product of the sector, requiring neither input of nutrients nor control over its reproduction cycle thanks to the special conditions of the warm water temperatures and high primary production of the estuaries.

Therefore, agro-food industries encompass a group of industrial activities aimed at transforming, manufacturing, preserving and canning foodstuffs, generally from raw vegetal or animal-natured materials. These industrial activities, as any other productive processes, show several features that have a great bearing on the environmental impacts they cause, as follows (Álvarez-Campana et al. 2004):

1. The exploitation of raw materials never achieves the 100%.
2. The necessary auxiliary materials in the manufacturing process, which are not incorporated in the final product, turn them into waste when they do not gather the essential specifications for their usage.
3. The specific operations of a productive process generate emissions.

This is the case of the marine aquaculture and seafood-processing industries that fulfil the above conditions by generating a huge amount of shell waste that could be environmentally sound recovered.

Since the mid-1970s, the EU's environmental policy has been articulated around action programs that establish priority objectives for a period of several years. The current program, which is the eighth of its kind, was approved by the European Parliament and the Council of the European Union and came into force in May 2022 and covers the period up to 2030 (EC, 2024d) The Program has helped to move towards a policy based on sustainable consumption and production. This highlights the importance of the Thematic Strategies on the Sustainable Use of Natural Resources and on the Prevention and Recycling of Residues (EC, 2024d), regulated through the Directive 2018/851/CE (EC, 2018) that repeals the Directive 2008/98/EC (EC, 2008a) on waste that includes specific obligations in this matter. Thus, the Member States would develop waste prevention programs with the ultimate objective of decoupling the waste generation from the economic growth. So, the kingdom of Spain has the obligation to have a Waste Prevention Program. On his behalf, Law 22/2011, of July 28, on waste and contaminated soils (Spanish Government, 2011), establishes in article 15 that public administrations, in their respective areas of competence, will approve waste prevention programs, in which the objectives of prevention and reduction of the amount of generated waste will be established (MAPAMA, 2017). These regulations and strategies on waste point to new opportunities to sustainable development, since they promote the application of environmental technologies and the recovery of waste in such a way they could be exploited as resources (COM, 2005).

However, this valorisation process is a source of odours owing to its inherent features. On the other hand, dimensions of nuisance odour provide a commonly accepted basis for the development of jurisdictional criteria of environmental odours (Brancher et al. 2017). Odours

emitted by food and waste valorisation industries are even more worrying the nearer the installations are to the residential areas. Nuisance odours are the result of an industrial process where the biological or chemical reactions give rise to odorous VOC (Volatile Organic Compounds) and are frequently accelerated by thermal treatments such as drying or calcination. Generally, the odour threshold in the surrounding area and the sensations it causes are very subjective.

The Integrated Pollution Prevention and Control regulation, the so-called IPPC Directive (EC, 2010) that was updated in 2010 and transposed to the Spanish legal framework by the law 5/2013 on 11 of June (Spanish Government, 2013a), has established a framework for assessing and regulating the most polluting industrial activities. The priority of this Directive is to achieve a high level of protection of the environment taken as a whole, especially by the prevention or, where not practicable, the reduction of pollutants, and thus, avoiding the transference from one medium to another (air, water and land). Specific processes that fall under the IPPC scope, like those carried out in plants for treating animal by-products, are required to determine their impact on several criteria, including odour impact. The industrial sectors involved are encouraged to define 'Best Available Techniques' (BAT) and 'Emission Limit Values' (ELV) at European level to achieve a greater efficiency in the environmental management and the performance of these facilities.

This chapter presents a plant dealing with mussel shell waste as input in its valorisation process, which is considered a priori an eco-friendly solution to the problem of disposal of this product. In fact, it is a clear procedure to turn waste into a high value-added product like lime, a secondary but sustainable raw material with a market potential to be used in different applications. However, as a result of the thermal treatment of the shell waste, odour emissions to the atmosphere become a serious problem. The pollution caused by these odours is creating an environmental and social conflict between the industry and the population of the surrounding area. Accordingly, this chapter aims to identify the sources of pollution to seek solutions and options for the prevention and control of odorous emissions from the installation. This is a new step in the greening process of the existing industrial activity.

5.1.1. Odour Management

The waste incineration activity in the EU is regulated by Directive 2010/75/UE (EC, 2010). It was transposed to the Spanish legal system by Royal Decree 815/2013 (Spanish Government, 2013b), which establishes the design, equipment, building and exploitation conditions for the incineration installations. However, materials as specific as the by-products derived from the mussel industry (mainly mussel shells) are not included into the scope of these regulations. The whole animal carcasses and parts thereof can be considered as unprocessed animal by-products and must be incinerated or co-incinerated in accordance with Regulation (EC) n° 1069/2009 (EC, 2009). This law sets the health rules concerning animal by-products not intended for human consumption. Should this waste be destined for incineration it will be regulated by law 22/2011 on waste, of July 28 (EC, 2013).

The shell, as part of an animal or product of animal origin not intended for human consumption, is considered a by-product, a category 3 material, as far as section j or section k (i) of article 10 is concerned according to Animal By-products Regulation (EC, 2009). It defines shells as the animal by-products of aquatic animals of establishments or plants that manufacture products for human consumption in section j or as a material of animal that does not present any sign of a disease transmissible to humans or the animals through said material, like mollusc shells stripped of soft tissue or meat. Consequently, their treatment has to comply with the specific provisions imposed by this law for this kind of material. Despite the extensive

regulations regarding animal by-products processing, the already mentioned legislation does not include any measure concerning atmospheric emissions control, although waste treatment processes are known to produce both chemical and biological emissions that can be perceived as odour (Aatamila et al. 2011).

Odours have been ranked as the major generators of public complaints to regulatory agencies in North American and European communities (Leonardos, 1995), and it has even been reported that in some European countries between 13% and 20% of the population is bothered by environmental odours (Hudon et al. 2000). These complaints are mainly consequence of the negative effects that prolonged exposure to foul odours can generate on people, causing reactions that range from emotional stress to physical symptoms (National Research Council Committee on Odors, 1979). In these situations, in which an odour is proved to have substantial negative impacts on the quality of life of a community, the odour emissions are considered to be a nuisance (Duffee, 1995).

Currently, there is no specific legislation on odours either in the EU or in Spain. However, efforts towards regulations addressing odour control are being made. One example is the "Horizontal Guidance for Odour" (UKEPA, 2002) from the UK Environment Agency. This is used as a reference for environmental permits in Europe, and also establishes some reference limit values for odorous emissions. Another European example is the "Netherlands Emission Guidelines for Air" (*Nederlandse emissierichtlijn lucht*) (Netherlands Agency, 2004), which proposes the application of emission-abating measures by implementing Best Available Control Technology for reducing air pollution with regard to the ALARA principle (As Low As Reasonably Achievable).

Spain has no specific instruments to legislate on odours at federal level. Generally, odours are treated subjectively in federal environmental laws. The Spanish regulation is still incipient in this regard, and is based on municipal ordinances or activity licences (Brancher et al. 2017). For this, air quality is ruled by Law 34/2007 (Spanish Government, 2007) that in spite of not including any specific regulation about odours, it establishes the bases for preventing, monitoring and reducing atmospheric pollution in order to avoid, and when not possible lessen the damage, they could cause to people and environment. The government of the Autonomous Community of Catalonia has been the first Spanish region to develop a draft (Generalitat de Catalunya, 2010) for a future law concerning odorous pollution. It started in 2005 and it is still being updated, as the latest draft version is from 2010. Although this does not fix any ELV, it establishes odour immission objectives for those areas requiring special protection, such as residential areas. These objective limits range between 3 and 7 ouE (European odour units) calculated as 98th percentile. Areas exceeding these values are considered to be odourously polluted, whereas immission values over 10 ouE cause nuisances to people. The draft also proposes reducing odours by implementing techniques candidate to be BAT, as well as good practices over the individual focus.

Against this lack of regulation on odours, some authors develop strategies to control and mitigate them. That is the case of Nicell (2009), who has proposed a framework for the regulation of odours that states that facilities that are identified as sources of potentially offensive odours shall ensure odours concentrations below 1 or 99,55% of the reference time, which is considered to be ten minutes. Other authors carried out studies to analyse the origin of odours in order to reduce them. For instance, Kim et al. (2008) measured emission concentrations of several compounds from various facilities located in a large industrial complex. They analyse their effect over odour pollution according to two major criteria, namely the industrial type and the source process unit. Another example is Cheng et al. (2009), who

performed several odour sampling campaigns after implementing different odour control measures to reduce dimethyl sulphide emissions.

5.2. CASE STUDY

The shell is produced as a rejected material in different marine aquaculture activities and seafood processing industries such as production companies, mollusc purification plants and boiling facilities and canneries. For the particular case of the mussel, the shell roughly represents between 31-33% of the total weight for this kind of molluscs used in the canning and processing installations aforementioned (Conservas Isabel Galicia S. L., 2006; Barros et al. 2009b). The shell is a composite biomaterial, for which the mineral phase, calcium carbonate, accounts for 95 to 99% per weight, whilst the remaining 1-5% represents organic matter (Barros et al. 2007a). This abundance of calcium carbonate in the shells can be exploited to be used for a wide range of applications.

The installation under study was a shell valorisation plant extracting calcium carbonate from mussel shells or other seashells by a thermal treatment to obtain commercial value-added products to be used in diverse applications. The plant, whose theoretical capacity was around 80,000 tons per year, was strategically located in Galicia, near the estuary of Arousa, in the north-western coast of Spain, to absorb the significant amounts of shell waste generated by the production centres located in the coastal areas of the region (Figure 5.1). It was placed in an industrial park taking up an area of 21,450 m². The built-up surface accounts for 5,120 m², where the production plant has 4,150 m² and eleven-meter high.

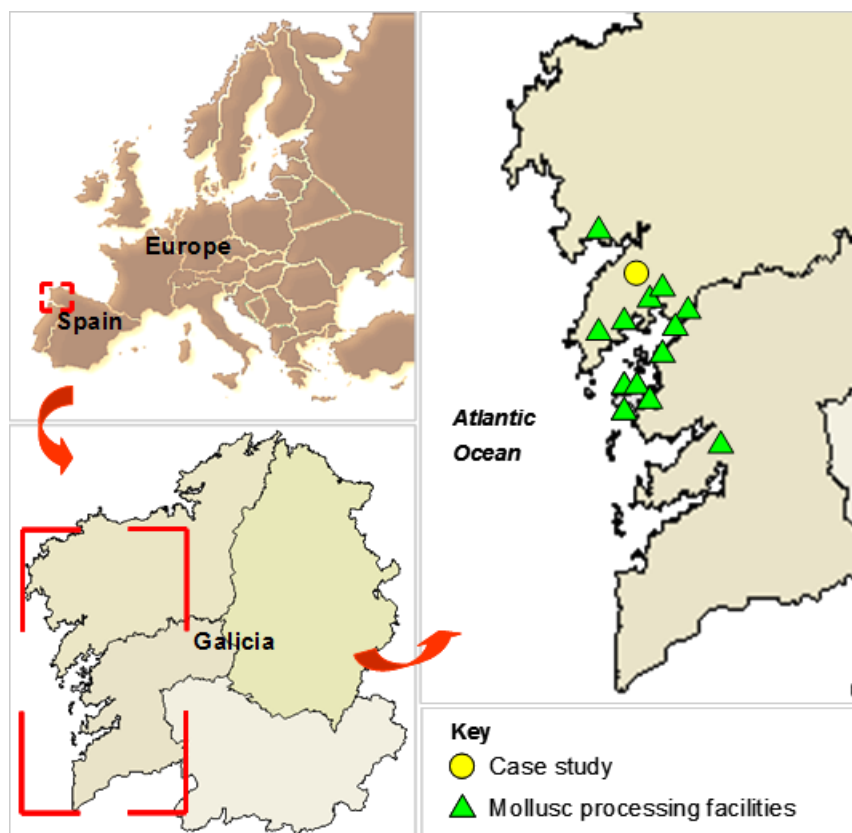


Figure 5.1. Geographical location of the installation under study and the shell production centres in Galicia

Since the beginning, the installation faced some general difficulties related to its environmental behaviour, but also specific problems related to odours, as the process uses as raw material an organic by-product, mussel shells, whose degradation results in odorous compounds among other pollutants. Aiming to improve the performance of the plant, the whole process was qualitatively analysed stage by stage, so that the potential Improvable Flows (IF) were identified and characterised. According to the results of this analysis, some techniques and good practices were proposed and implemented through a first five-year period aiming to “green the process”. After this first period, as odour problems persisted, it was suggested a deeper study whose main objective was to qualitative and quantitatively identify and define the potential odour sources in order to select the most appropriate techniques to avoid odour emissions.

5.3. METHODOLOGY

The method used in this chapter includes three main steps as indicated below.

1. Greening the process. The whole plant was subjected to a greening process due to several facts: a) as a response to the first environmental problems detected in the plant, b) the growing awareness on the impact of emissions over the surrounding areas and, c) supported by the implementation of more restrictive regulations. It implied a deep qualitative analysis of the process following the methodology described by Barros et al (2009a). It continued with the proposal and implementation of several techniques and good practices addressed to improve the environmental performance of the installation. Key improvements were carried out during five years (first period) to reduce the polluting emissions and improve the working conditions in the plant. These results are explained in detail by Barros et al. (2009b).
2. Olfactometric analysis. This technique was proposed and implemented in 2007 owing to the persistence of the odour pollution in the plant. It includes three sub-stages:
 - a. Qualitative analysis. Identification and justification of the potential odour sources of the plant, according to the process description included in the previous stage (Barros et al. 2009b).
 - b. Quantitative analysis. Sampling in the identified sources and analysis of the samples according to the European Standard EN 13725 (UNE, 2011). Odour and odorous compounds emissions, namely as VOC (Volatile Organic Compounds), NH_3 , H_2S and R-SH , were quantified.
 - c. Immission analysis. Passive sampling in selected locations (inside the plant and in its surrounding area) to determine the immission concentrations of VOC and NH_3 .
3. Results. Evaluation and discussion of the results of the olfactometric analysis. It includes two sub-stages.
 - a. Detection of improvable flows. According to the results obtained from the quantification of emissions, the most likely flows to be improved are identified and ranked according to their contribution to the total odour emissions of the plant.
 - b. Identification of solutions. Techniques and good practices aiming to avoid, or at least reduce, odour emissions are proposed to each of the identified improvable flows.

5.3.1. Greening the Process

Greening the shell valorisation process solved several major problems that the plant was facing at that time (Barros et al. 2009b). During a first five-year period, eighteen techniques and good practices aiming to improve the environmental performance of the plant were proposed and applied with quite satisfactory results since emissions of some pollutants (mainly dust, CO and VOC) were greatly reduced. Amongst the measures implemented during these years, five of them specifically referred to odour emissions:

1. Use of fresh mussel shells as raw material, to reduce the grade of decomposition and minimise VOC releases.
2. Hoppers with automatic doors permanently closed, except for loading and unloading. The material should be processed in the same day of its reception.
3. Periodic water-cooling of the washed shells stored in the silos to avoid fermentation and VOC releases. Three days will be the maximum storage time in silos.
4. Substituting the existing wet scrubber with a more efficient abatement technique. When inherently malodorous substances are produced during the calcination of the shell, the low intensity/high volume gases should go through some abatement equipment, such as a biofilter or an oxidiser, to clean the gas stream where odour prevention is not reasonably practicable. There are several devices to treat VOC emissions that should be considered to collect the waste gas stream by an extraction system prior to the end of pipe treatment. They are divided into recovery techniques, such as membrane separation, condensation, adsorption and wet scrubbers for gas removal and, abatement techniques such as biofiltration, bioscrubbing, biotrickling, thermal or catalytic oxidation and flaring (EC, 2016a). The technique chosen for the plant was a regenerative oxidiser (Figure 5.2), given the nature of the waste gas stream from the kiln. Besides its content in organic substances (carbon monoxide, VOC and others), the existence of ashes made necessary a bag filter prior to the abatement equipment to firstly scrub the exhaust gases. Thus, both equipments assure not only the removal of particulate matter from the gaseous stream (less than 10 mg/N m^3), but also the destruction of any existing VOC at temperatures of $800\text{-}1000^\circ\text{C}$ inside the combustion chamber (efficiency higher than 95%).



Figure 5.2. Bag filter and regenerative thermal oxidiser

5. Monitor all sources of fugitive emissions. Despite the olfactory aggressiveness of some odorous emissions, their concentrations are usually below the detection level of conventional chemical analyses. This measure is deeply developed in the next stage of the methodology

5.3.2. Olfactometric Analysis

Determining the odorous compounds is a complex process, as the odour potential of a compound depends on objective aspects such as volatility and solubility, and subjective ones such as physiological and psychological characteristics of the receptor (Bruno et al. 2007). Olfactometry is a technique for sampling and analysing odours, coupled with dispersion modelling, which allows evaluating the nuisance caused by odours and determining their origin. Olfactometric studies are a useful tool to control and reduce odours emitted by different types of sources as they do not only determine the degree of nuisance created in the environment, but also identify odour sources. This permits the adoption of effective elimination or reduction measures.

The olfactometric analysis performed at the installation includes three stages that will be discussed below, namely qualitative, quantitative and immission analysis.

5.3.2.1. Qualitative Analysis

A general flow sheet of the valorisation process is shown in Figure 5.3 as part of the mussel shell life cycle from the reception of the mussel shell to the exit of the CaCO_3 . The valorisation process carried out in the plant can be divided in three main stages, such as preliminary operations, processing and auxiliary operations. Preliminary operations consist in the reception and unloading of the raw materials, in addition to those operations involving the elimination of salt and mud contained in the shells and the storage prior to their processing. Processing involves the thermal treatment of the shells and the subsequent cooling of the burnt material and, finally, auxiliary operations, which are additional operations such as milling and sorting, that prepare the final product for marketing. Other operations are the final product storage and its packing and shipment.

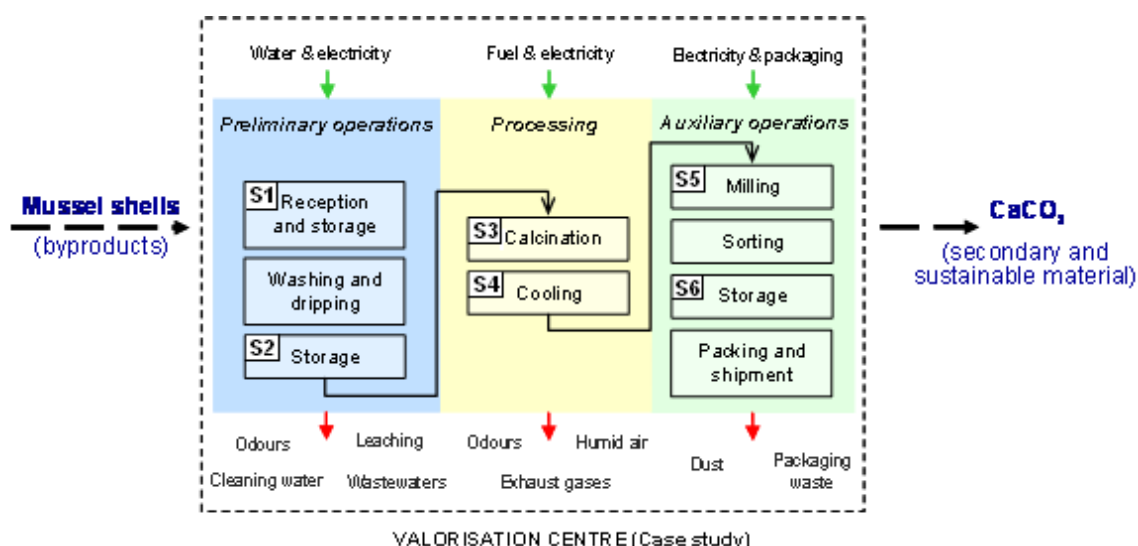


Figure 5.3. Flow sheet for the mussel shell valorisation process. S1 to S6 indicate the sampling points for quantitative olfactometric analysis in Table 5.2

Considering the analysis of the process developed in a previous work (Barros et al. 2009b), the potential odour sources have been qualitatively identified. They mainly correspond to the storage of raw material prior to its processing and to thermal treatments, where VOC derived from the destruction of the organic fraction are released. The selected points, as well as their effect over the odorous emissions released by the plant, are described below:

1. Reception and storage. Raw mussel shells are unloaded in two ground-level reception hoppers where they remain until they are processed (the same day they are received). The transport of raw materials from the production centres to the valorisation plant strongly influences the emission of odours. A key parameter to consider is the shell lifetime at the time of collecting, as it has a remarkable importance in the degradation state of the waste. The flesh attached to the shell is highly perishable and generally requires either rapid storage and containment or quick processing to avoid decomposition and, consequently, odour emission and dispersal of pathogens. Other parameters to take into account are the climatic conditions (sunny and hot weather favours faster reactions), as well as the cleaning of the vehicles and the storage time of the shell in the production centres.
2. Washing and dripping. This step consists in cleaning the shell with freshwater to reduce the salt content of the final product, avoid the wear of the equipment by corrosion and obtain a more concentrated product of CaCO_3 . Therefore, it is very demanding on water and accounts for 80-90% of the total water consumption inside the installation. This activity is carried out in two rotary washing machines operating counter currently to increase the performance of the salt extraction. Afterwards, there is a shaker draining rack to remove the water dragged by the product. Then, wastewaters and mud waste go to the on-site Wastewater Treatment Plant (WWTP) where they undergo a physicochemical treatment.
3. Storage. After washing, clean mussel shells are stored while they complete their dripping in stainless steel silos that are loaded by gravity and unloaded by a vibrating system to favour the thermal treatment. The washed shells stay here at most for three days. The leachates generated here are channelled to the WWTP for its treatment. Odours released in this stage are mostly related to the dripping of the washed shells, which generates leachates containing some remains of the dirt and organic matter that embedded the raw mussel shells received in the plant.
4. Calcination. Mussel shells are burnt in a counter-current rotary kiln that integrates two processes, drying and calcining, in a single piece of equipment. The kiln, whose production capacity is 18 tons per hour, is 17 meters long and 2.5/3.0 meters diameter, and it is divided in three sections (Figure 5.4). The residence time of the material depends on the spin velocity of the kiln, but it ranges between 20-30 minutes. Four thermocouples (T1-T4) register and monitor the temperature in different sections inside the kiln.

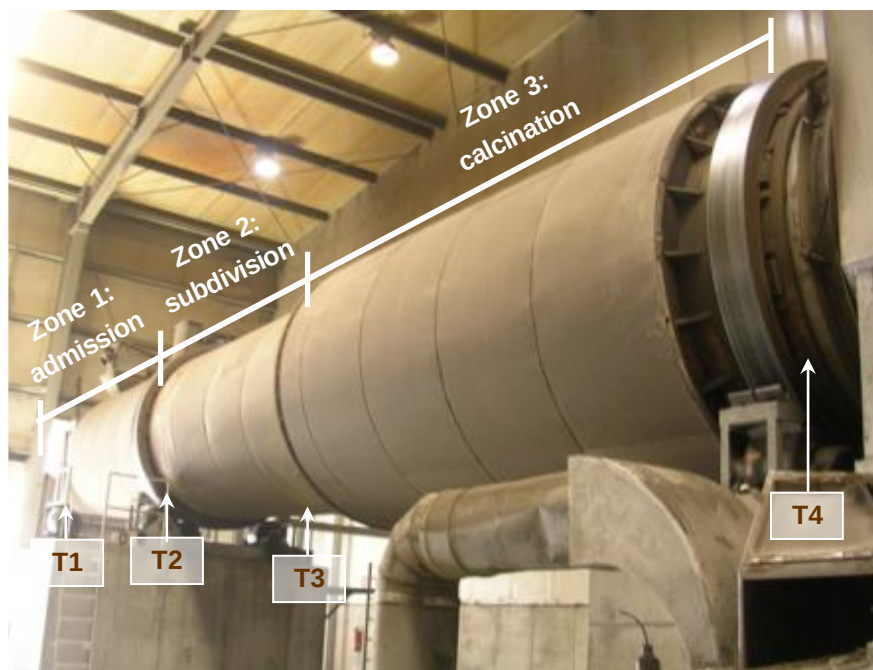


Figure 5.4. Rotary kiln. The four thermocouples indicate the following temperatures: T1 (125-250°C), T2 (225-250°C), T3 (300-325°C) and T4 (475-500°C)

Calcination is an important source of odours since its operating temperature ranges between 125-500°C. This is not enough to destroy odorous compounds, as incineration processes with temperatures below 850°C can result in odour emissions (EC, 2006). The gases emitted by the kiln during the analysed mussel shell valorisation process show the following features:

- a. Volume of flow: 14,000 Nm³/h
- b. Temperature: 130-150°C
- c. Moisture: 17% (vol.)
- d. VOC (as TOC (Total Organic Compounds)) concentration: 650 mg/Nm³

In spite of being hardly detectable concentrations of organic substances, the released gases are aggressive olfactory emissions of an intense and unpleasant smell and with high temperatures. As a result of the “greening the process” stage, an abatement technique for odorous compounds was implemented. This technique combines a bag filter, which assures the removal of particulate matter from the gas stream (<10 mg/Nm³), with a regenerative oxidiser that destroys more than 95% of the VOC operating at temperatures that range between 800-1000°C.

5. Cooling. The burnt material is cooled down from 500-600°C to 60°C through a two-step process. It begins with the injection of thinly dispersed water to reduce temperature from 500-600°C to 170-190°C, and finishes with air refrigeration, that completes the reduction of the temperature from 170-190°C to 60°C.

Both the leachates from water injection and the refrigeration air could drag some organic compounds still stuck to the burnt shells that may result in odour emissions.

6. Milling. Milling is aimed at crushing the shell to obtain products with purity levels of 90-95% in CaCO₃ and different sizes of particle that will determine its industrial application. This stage includes diverse operations to obtain different particulate sizes (Table 5.1), namely grinding, screening and micronizing.

7. This process mainly generates dust and particulate matter emissions that are conducted to the dust abatement equipment that recovers dust and reincorporates it to the process. Besides dust, VOC can also be released during milling processes. Mostly because of some remains of organic compounds that were not totally destroyed during the thermal processes.
8. Storage. After sorting the milled shells according to their particulate size, the sorted fractions of the final products are stored in three adjustable hoppers with regard to its grain size. From them, the products can be stored either in two enclosed warehouses or in silos depending on the final use of the product or the packaging format in which it is marketed.

Despite the high quality of the final product (90-95% of CaCO_3), some VOC can still be released during storage.

Packing and shipment. The final products are packaged in bulk (tanks or containers) or big bags of 35 kg and 1 ton, and shipped off for sale.

Table 5.1. Particle size related to milling operations

Milling operations	Particle size (diameter)
Grinding	0-8 mm
Screening	<2 mm
	2-4 mm
	>4 mm
Micronizing	<63 μm

5.3.2.2. Quantitative Analysis

The quantitative olfactometric analysis was done according to the procedure described by the European Standard EN 1372:2004 ERRATUM:2011, Air quality – Determination of odour concentration by dynamic olfactometry (UNE, 2011), which provides a reference method for sampling and assessing odours, whose concentrations are calculated and expressed in European odour units (ouE/m^3).

The sampling points (S1 to S6) shown in Figure 5.3 correspond to the qualitatively identified potential odour sources (Table 5.2).

The samples taken from the identified sources were analysed by dynamic olfactometry, procedure PE-OLF/007 (UNE, 2011), which resulted in odour concentrations for each sample in ouE/m^3 (Table 5.3). From these results, the punctual odour emissions (ouE/h) were calculated using data about the gas flows and the exposed area in each focus. Furthermore, for all the odour sources, sulphide, ammonia and mercaptan concentrations were assessed with Dräger colorimetric tubes. Ammonia results were confirmed by measurement with a specific electrochemical detector, Gas Alert Micro 5Pid (BW Technologies, Calgary, Canada).

Table 5.2. Process stage points sampled for the quantitative olfactometric analysis

Sample	Process stage
S.1	Reception and storage
S.2	Storage (in a silo)
S.3	S.3.1
	S.3.2
	Calcination (exhaust gases from the thermal oxidiser)
S.4	Cooling
S.5	Milling (shed)
S.6	Storage (shed)

Table 5.3. Odour emissions and odorous compounds emissions in the sampled points

Sample	Total flow (m ³ /h)	Odour concentration (ouE/m ³)	Punctual odour emissions (ouE/h)	Concentration (mg/Nm ³)		
				NH ₃	H ₂ S	R-SH
S.1	1,436.00	228.00	0.33	<0.25	<0.20	<0.50
S.2	1,044.00	512.00	0.50	4.00	<0.20	<0.50
S.3.1	15,751.00	96,755.00	1,524.00	634.00	<20.90	<52.30
S.3.2	16,272.00	89,276.00	1,453.00	714.00	<20.90	<52.30
S.4	15,906.00	<1,845.00	<29.30	<0.25	<0.20	<0.50
S.5	17,848.00	51.00	0.90	<0.25	<0.20	<0.50
S.6	41,324.00	181.00	7.50	2.00	<0.20	<0.50

For sample 3 (S.3.1/2), considering the odour concentrations obtained for each sample, an average odour concentration value is calculated, resulting 93,015 ouE/m³. The airflow is calculated considering the gases output velocity and the section area in the sampling point. The gases output temperature was 174.2°C and 180.3°C respectively, and the pressure 1,013 mbar. The average odour emission calculated using the data obtained for both samples is 1,488 ouE/h.

The characteristics of the mussel shell drying/calcining gases depend on the nature of the VOC they contain. Thus, the odours they release can be different in type and intensity. The gas stream resulting from the drying/calcination stage has been analysed to identify the most abundant and odorous VOC present in the gases released during the thermal treatments. The analysis focuses on the most odorous compounds shown in Table 5.4, where two different samples are compared:

1. Sample A, taken and analysed in 2004, before implementing the abatement equipment for the gas stream of the kiln (bag filter – regenerative oxidiser). The sample corresponds to the gas stream emitted by the calcination kiln.
2. Sample B (duplicated), as part of the present sampling, taken after implementing and operating the bag filter and the thermal oxidiser. The samples correspond to the gas stream emitted by the thermal oxidiser.

Table 5.4. VOC concentration in samples taken before and after implementing the thermal oxidizer

VOC	Concentration (mg/Nm ³)		
	Sample A	Sample B.1	Sample B.2
1,1-dichloroethene	-	3.270	6.380
Trans-1,2-dichloroethene	-	23.500	7.520
Benzene	4.070	5.930	5.000
1,2-dichloropropane	-	<0.100	1.370
Toluene	1.850	17.900	15.200
Tetrachloroethylene	0.036	<0.100	<0.100
Ethylbenzene	0.038	5.640	2.990
m,p-xylene	0.071	6.220	12.300
o-xylene	0.025	1.220	2.240
Styrene	0.017	0.640	0.380
Isopropylbenzene	-	0.120	1.060
1,2,3-trichloropropane	-	<0.100	0.580
n-propylbenzene	-	0.160	2.510
1,3,5-trimethylbenzene	0.005	0.220	0.840
Carbon disulfide	0.180	<0.100	<0.100
Ethyl acetate	<0.00005	<0.100	<0.100
Butyl acetate	<0.00005	<0.100	<0.100
1,2,4-trimethylbenzene	-	1.050	2.480
Dimethyl disulfide	1.570	<0.100	<0.100
α-pirene*	0.024	2.460	76.700
Hexane	0.128	-	-
C ₄ H ₆ (probably 1,3-butadiene)	1.950	-	-
Acetone	3.870	-	-

The gas output from the drying/calcination process in the case study is composed by a big amount of substances (mainly VOC) characterised by their odorous intensity, and with really low odour thresholds. The analysis results show quite high concentrations of some VOC, such as benzene, acetone, toluene and C_4H_6 . For most of the compounds, the concentrations were found to be $<0.10 \text{ mg/Nm}^3$, although for some other compounds the concentrations were quite higher (Table 5.4).

As it can be seen in Table 5.4, the observed differences in the results of VOC emissions in 2004 and 2007 samples indicate malfunctions, not adequate techniques or abnormal operating conditions, among others.

5.3.2.3. Immission Analysis

Passive sampling was used to determine the immission concentrations of VOC and ammonia in different locations. The procedure used for sampling was UNE-EN 13528-1/2, ambient air quality: diffusive samplers for the determination of concentrations of gases and vapours (UNE, 2011). Twelve sampling points were selected from the plant and its perimeter to evaluate the effect of odorous compounds over the environment. The sampled points were:

1. P1: Truck unloading area
2. P2: Perimeter fence (close to entrance)
3. P3: Outer road
4. P4: Perimeter fence (close to fuel tank)
5. P5: Outflow of the air conditioner of the offices
6. P6: Reception
7. P7: Silos ship (6 m high)
8. P8: Silos ship (12 m high)
9. P9: Calcination ship
10. P11: Final product storage ship
11. P12: Sewage

Ammonia was determined by water sensor extraction according to the Radiello protocol followed by indophenols colorimetric analysis (Spectrophotometer Shimadzu UV-1603). On the other hand, VOC samples are taken with a graphitized carbon cartridge, which thermally desorbs using a thermo-desorption system directly coupled to a gas chromatography (Agilent 6890N) mass spectrometry detector (Agilent 5973).

The immission results (Table 5.5) show quite high NH_3 concentrations, especially in those sampling points where process equipment is located. The same applies to VOC emissions, although sampling point P4 shows quite big immission concentrations of certain VOC, owing to the fact that fuel is stored in that area. These results show that although VOC and NH_3 concentrations may be quite high in the areas where the proper process takes place, they are reduced with the distance.

Table 5.5. Immission concentrations of VOC and NH_3

Compounds		Immission concentration ($\mu\text{g}/\text{m}^3$)										
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P11	P12
VOC	Toluene	-	*	1.51	0.06	0.21	10.20	0.92	263.00	6.29	8.80	2.48
	Benzene	-	*	0.05	0.19	0.25	2.44	0.17	11.70	3.26	1.90	0.31
	Ethyl-benzene	-	*	1.27	16.00	0.47	3.67	5.54	195.00	1.47	3.08	2.37
	m,p-xylene	-	*	0.21	10.50	0.79	4.96	2.45	124.00	9.93	2.84	3.04
	o-xylene	-	*	0.92	10.90	0.43	3.07	8.56	232.00	7.67	1.38	4.23
	Styrene	-	*	0.47	0.99	1.25	25.70	0.32	3.27	49.10	15.20	0.84
NH_3		69.40	0.10	4.00	24.50	-	57.60	55.80	53.60	63.50	56.90	6.50

* Problems in the chromatograph injector made it impossible to analyse the sample.

5.4. RESULTS

5.4.1. Detection of Improvable Flows

According to the results obtained from the olfactometric analysis (Table 5.3), the most important odour sources are the thermal treatments, as calcination has been pointed out the most odorous process by far. The storing areas are the next most odorous sources, being the storage of the raw materials more odorous than the storage of the final products. Finally, the analysed stage generating less odour emissions is milling. This ranking is supported by the results obtained from the analyses of NH_3 , H_2S and R-SH concentrations, as calcination showed by far the highest concentration for all the compounds, whereas the rest of the sampled processes presented concentrations below the range in most of the cases. Consequently, calcination is the most important improvable flow detected in this process, as the odour concentration of its gas stream is more than fifty times bigger than the next most polluting source, namely cooling. However, in spite of these great differences between the sampled points, none of them are negligible when compared with the “relative offensiveness of odours” proposed in the Horizontal Guidance for Odour (UKEPA, 2002). Here it is suggested that offensive odours, such as the ones derived from activities involving putrescible waste or from processes involving animal or fish remains, can cause annoyances if they exceed 1.5 ouE/m^3 98th percentile (hourly average concentration for odour measured at the nearest odour sensitive receptor beyond the facilities boundary), which is by far exceeded by all the analysed samples.

The stages likely to generate some leachates have been found to be quite odorous, as storage after washing (where the raw materials drip water), reception and storage of raw materials and cooling. According to this conclusion, the wastewater treatment plant should have been included as an out of process sampling point, as it may be a potential odour source. But its odour emissions have not been included into the scope of this paper because it is only focused on the mussel shell valorisation process itself. However, some techniques and good practices will be proposed to mitigate odour emissions from the wastewater treatment plant.

5.4.2. Identification of Solutions

Although diverse technologies to control odour nuisances have been developed or improved (EC, 2005), the best method to manage this type of emissions is the elimination of the odorous components before their formation, thus avoiding a further treatment of the waste gas stream. Nonetheless, most of the waste valorisation installations cannot have an exhaustive control over all the VOC emitted during their processes.

Considering the improvable flows detected after evaluating the results of the olfactometric analysis, some measures and alternatives aiming to prevent and/or limit the odours in the installation have been selected and proposed for their implementation in the plant. They are classified according to the process stage where they should be applied.

5.4.2.1. Reception and Storage of Raw Materials

- 1 Collect the shells as soon as possible after their production. This measure can be easily implemented due to the strategic position of the objective plant with regard to the production centres (Figure 5.1), so the shell arrives to the plant within 48 hours after its rejection.
- 2 Raw materials should be transported in hermetically sealed containers to prevent the emission of liquid effluents. Waste should be saved dry whenever possible to avoid increasing odour problems.

- 3 Containers, packaging and vehicles used for transporting unprocessed material must be cleaned in a specifically designed area.
- 4 The floor in the storage facilities should be waterproof and extraction systems should be installed to collect residual gases for further treatment.
- 5 Installations and equipment must be regularly cleaned and disinfected.
- 6 Preventing anaerobic conditions by aeration, turning of waste and short timescales (UKEPA, 2002).
- 7 Reduce temperature during storage by avoiding direct sunlight or otherwise reducing the water evaporation rate and the release of dissolved odorous chemicals (UKEPA, 2002)
- 8 Minimise airflow over the surface of odour-releasing materials, which also reduces the rate of evaporation (UKEPA, 2002).
- 9 The shells must be processed immediately after their arrival to the plant, otherwise stored properly until processed in enclosed buildings with sealed hoppers to avoid the emissions outside the facilities. In the plant, the maximum storage time in the hoppers is the same day they are received to avoid the decomposition of the remaining flesh attached to the shells.
- 10 The shells are stored in silos up to three days after washing to avoid fermentation processes and the release of odours. But if fermentation occurred, the shells should be washed to control the achievable temperatures (up to 70°C).

5.4.2.2. Thermal Treatment

- 1 The shell must be placed straight in the kiln without any direct handling in order to prevent kiln opening during loading operations that favours the release of residual gases. The input of shell to the kiln is done and regulated by a dosing machine.
- 2 Adjust the main parameters of the process, such as temperature, duration, pressure or venting, to reduce formation and/or release of odorous compounds (UKEPA, 2002).
- 3 Contain odorous air within process machinery to avoid contaminating larger volumes of ventilation air within buildings, which can consequently reduce the cost of air treating (UKEPA, 2002).
- 4 Enclosing odorous waste all the way to the thermal treatments stage (UKEPA, 2002).
- 5 Drawing air from odorous areas at a rate that will ensure that odour is captured and feeding, as far as possible, odorous air into the combustion process (UKEPA, 2002).
- 6 Control the temperature up to 850°C ensuring that is maintained at all times during operation and as long as unburned material is inside.
- 7 The gas resulting from the process is heated, in controlled conditions, to a temperature of 850°C for two seconds. As previously explained, the temperatures inside the combustion chamber achieved this figure.

5.4.2.3. Final Product Management

- 1 Avoid odours emissions by keeping windows and doors shut in process building, by implementing remotely operated roller doors that reduce the time that doors are open or by maintaining negative pressure within the process plant (UKEPA, 2002).
- 2 Good housekeeping to avoid the appearance of malodorous materials and wastes except in designated (and appropriately managed) areas (UKEPA, 2002).
- 3 Suitable and sufficient staff training with regard to odour control. Staff should also be aware of relevant licence conditions and emission limits in its work (UKEPA, 2002).
- 4 Buffer zones in areas where odour is emitted at low level (UKEPA, 2002).

5.4.2.4. Waste Water Treatment Plant (WWTP)

- 1 Prevent wastewater stagnation by laying the pipelines related to the WWTP with a certain inclination.
- 2 Subject the leachates and the effluents to a biological treatment process, aerobic or anaerobic. At present, the treatment carried out in the plant consists on a physicochemical treatment including solid screening, homogenization and dissolved air flotation, where the flocculation-coagulation processes take place. Once the flocculates are separated, they are transferred to a sludge pit and then they are thickened and dewatered in a centrifuge. However, these processes are not enough to comply with the emission values set by the Competent Authorities due to the high organic load in the wastewaters. For this reason, a biological stage of nitrification-denitrification is planned to be included in the WWTP for further treatment of the wastewaters. This stage is currently starting up and no data is available, but it is expected to meet the allowable discharge limits. Furthermore, water consumption in the most water-demanding step, the washing of shells, is minimised as cleaned water is fed back to this operation.

5.5. CONCLUSIONS

The case study of this chapter is a pioneering industrial activity on thermal valorisation of mussel shells reutilizing wastes as resources. This makes every unexpected technical fault is faced up to without any previous background. Therefore, the organisation is a source of new experiences regarding technological development.

Getting the environmental permit required to operate according to the provisions of the IPPC is a driving force to audit and monitor odour emissions, reduce their generation to the surrounding area by means of the aforementioned measures and best environmental practices and upgrade the operating conditions of the equipment and the facilities. Nevertheless, despite the efforts carried out over the years in order to improve the productive process, hard work is still going to be addressed to prevent and/or control the environmental impacts derived from shell valorisation.

In spite of the variety of prevention and abatement alternatives proposed, odour problems are better dealt with at source, by means of process design or modification, or even managing the activity differently (UKEPA, 2002). Therefore, the best odour management program for the process analysed, mussel shell valorisation, should include a complete re-design of the process, taking into account the conclusions extracted from this chapter, which has pointed out thermal treatments as the most odorous processes, followed by raw materials storage. Operating procedures should also be updated to eliminate those practices that can affect the total odours emissions released by the plant.

CHAPTER 6. TOWARDS SUSTAINABLE MOBILE SYSTEMS CONFIGURATIONS: APPLICATION TO A TUNA PURSE SEINER

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

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SUMMARY

Fishing is one of the most important marine activities. It contributes to both overfishing and marine pollution, the two main threats to the ocean environment. In this context, the aim of this chapter is to investigate and validate methodologies for the identification of more sustainable operating configurations for a tuna purse seiner. The proposed methodology is based on a previous one applied to secondary industrial systems, taking into account the Integrated Pollution Prevention and Control focus, developed for the most potentially industrial polluting sources. The idea is to apply the same type of methodologies and concepts used for secondary industrial punctual sources, to a primary industrial mobile activity. This methodology combines two tools: “Material and Energy Flow Analysis” (a tool from industrial metabolism), and “Best Available Techniques Analysis”. The first provides a way to detect “Improvable Flows” into the system, and the second provides a way to define sustainable options to improve them.

Five main Improvable Flows have been identified in the selected case study, the activity of a purse seiner, most of them related with energy consumption and air emission, in different stages of the fishing activity. Thirty-one Best Available Techniques candidates for the system have been inventoried, that potentially could improve the sustainability of the activity. Seven of them are not implemented yet to the case study. The potential improvements of the system proposed by this chapter are related to energy efficiency, waste management, prevention and control of air emissions. This methodology demonstrates to be a good tool towards sustainable punctual systems, but also towards sustainable mobile systems such as the fishing activity in oceans, as the tuna purse seiner validated here. The practical application of the identified technologies to fishing systems will contribute to prevent and reduce marine pollution, one of the greatest threats of today's oceans.

6.1. INTRODUCTION

Oceans cover about 71% of Earth's surface to an average depth of 3700 m (Pörtner et al., 2014); and comprise more than 90% of the living biosphere by volume (Worm and Lotze, 2016). Oceans create half the oxygen (O₂) we use to breathe and burn fossil fuels (Pörtner et al., 2014). The seas regulate the global climate by serving as an enormous thermal mass for heat storage and as a reservoir for CO₂ (Constanza, 1999). The health of the ocean therefore has direct implications for all life on Earth (Rashid Sumaila et al., 2016). The ocean provides humanity with both living and non-living natural resources such as food, materials, essential substances, and energy (Visbeck et al., 2014). Oceanic resources and services are essential for human life and prosperity and unless effectively regulated, various oceanic resources and services are at risk of overexploitation (Rickels et al., 2016). However, resources are limited due to the tax of renewability, and fishing activity is a potential source of impacts especially in the marine environment. Therefore, it is very important to make sustainable use of marine resources, along with good management of them, and specifically related to fishing activity, eliminate or minimise the environmental impacts as much as possible (FAO, 2017).

In the Ocean, consequences of human activities can be observed as global fish stock declines, extinct or threatened species, habitat loss, pollution, invasive species, ocean warming and acidification, among others (Lotze et al., 2018). According to the final report of the Global Ocean Commission (2014): “Our Ocean is in decline. Habitat destruction, biodiversity loss, overfishing, pollution, climate change and ocean acidification are pushing the ocean system to the point of collapse”. The FAO (Food and Agriculture Organization) states that direct human interventions at regional scale comprise the introduction of non-native species, overfishing, pollution, long-range atmospheric transport of nitrogen, point-source eutrophication, and habitat destruction (FAO, 2017). It is not clear how much of the present changes in the oceans are being caused by anthropogenic climate change or natural climate variability, fishing, pollution, etc. It is known, however, that the resilience of marine ecosystems to adjust to these impacts is likely to be reduced, but the current rate of changes is much faster than most changes in the Earth's history; therefore, predictions from longer-term geological records may not be applicable if the changes occur within a few generations of species (Pörtner et al., 2014). Fishing activity is one of the most important economic activities in the World, source of wealth and employment (CEPESCA, 2015). At the end of last century, Jennings and Kaiser (1998) said that fishing is the most widespread human exploitative activity in the marine environment. According to United Nations (UN) Food and Agriculture Organization, in 2006, 25% of global fisheries were overexploited, depleted, or recovering from depletion. In the same year, a study in science predicted that all fisheries would collapse by 2048 (Chatterjee, 2009). At present, the FAO (2016) argues that the populations of the central-western Atlantic are in an untenable situation from the biological point of view, while 56% are within the limits of biological sustainability. Besides overfishing, marine pollution influences ocean conditions. This activity is regulated by the MARPOL (Marine Pollution) Convention (International Convention on the Prevention of Pollution from Ships), adapted in 1978 by the International Maritime Organization (IMO), the key United Nations institution for the development of international maritime law (IMO, 2002). Its main role is to create a regulatory framework for the shipping industry that is fair and effective. This framework, universally adopted and implemented, includes rules for prevention and reduction of ship pollution (UNO, 2017). Ships are major emitters of air pollutants such as sulphur dioxide and nitrogen oxides and their contribution to the emissions from the transport sector is growing (Schembari et al., 2012). International ships are usually powered by diesel engine system. Nitrogen oxides (NO_x), sulphur dioxide (SO₂), particulate matter (PM), carbon monoxide (CO) and carbon dioxides (CO₂) are the major

pollutants emitted from vessel engines during the combustion; moreover, SO₂ emission from ships not only reduces the local and regional air quality but also affects the marine sulphur cycle and the climate (Yau et al., 2012).

Gaseous emissions are not the only source of pollution in the ocean; there are a lot of wastes such as oil, nets, litter, wastewater and so on, that are discharged in the ocean from different type of sources. Approximately, both fishing activity and maritime transport contribute to marine pollution by 12% (Clark, 2002). A big example is marine litter, where plastics are by far the most common component. Plastic is associated with chemicals that accumulate onto their surface, and may act as a source of toxic substances that can be lethal to marine life (Urban-Malinga et al., 2018). Millions of tonnes of plastics end-up in the ocean, representing approximately 80%, and between 10 and 30% provides from fisheries (EC, 2017a).

Independently of such threats and the overall importance of the ocean in providing various services, the mitigation of current and future marine environmental problems and approaches to sustainable use, and the development of marine resources have been accorded only very low priority in many states (Visbeck et al., 2014). So, in the exercise of making a sustainable use of sea resources, fishing activity plays a very relevant role.

Tuna fishing is one of the most important fishing activities in the Ocean due to its significant economic impact and as source of food. This fishery comprises forty commercial species fished in the Pacific, Atlantic and Indian Oceans, as well as in the Mediterranean Sea. Table 6.1 shows the seven most fished tuna species, as well as the corresponding fishing rate (FAO, 2017).

The International Commission for the Conservation of Atlantic Tuna (ICCAT) is responsible for the conservation of tuna and tuna-like species in the Atlantic Ocean and adjacent seas. Tuna fishing is carried out with a wide range of fishing gears, especially purse seine (Davila Fernandez, 1985). Figure 6.1 displays the catches by fishing gear, from 2000 to 2016. In general, in 2008 a general decrease is observed, but immediately only the species captured by purse seine begin to ascend (ICCAT, 2017), being this fishing technique the most relevant at the moment.

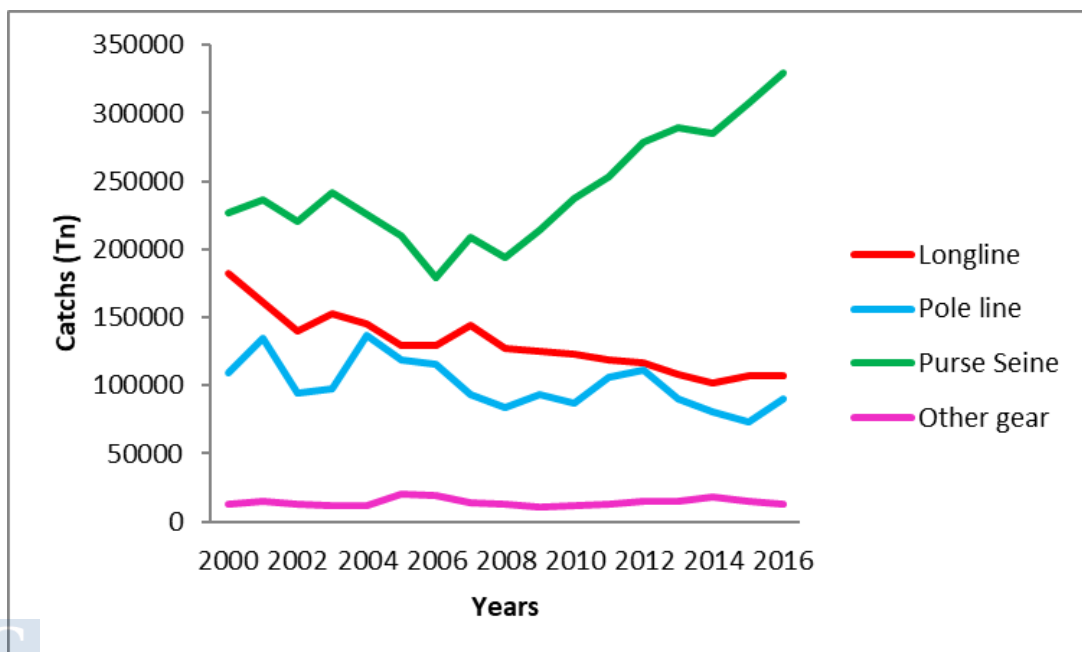


Figure 6.1. Tuna catches in ton with different fishing gears from 2000 to 2016 (ICCAT, 2017)

Table 6.1. Most economically important species of tuna (FAO, 2017).

PHOTO	SPECIES	RATING
	Albacore Tuna (<i>Thunnus alalunga</i>)	5.9 %
	Northern Bluefin (<i>Thunnus thynnus</i>)	<1.0%
	Bigeye Tuna (<i>Thunnus obesus</i>)	8.2%
	Bluefin Tuna (<i>Thunnus orientalis</i>)	<1.0%
	Southern Bluefin (<i>Thunnus maccoyii</i>)	<1.0%
	Skipjack Tuna (<i>Katsuwonus pelamis</i>)	58.1%
	Yellowfin Tuna (<i>Thunnus albacares</i>)	26.8%

The purse seine consists on a square net with floats in one side and weights in the other side, which keeps the net in a vertical position. The net can be closed in the bottom side pulling a rope along rings which are drawn closer to one another, preventing the escape of the fishes from the net. The fishing process starts when the net is launched with a barge and the shoal is surrounded with the purse seine. Afterwards the purse seine is closed and the shoal is trapped.

6.1.1. Sustainable systems evaluation tools and industrial ecology

Industrial ecology is a holistic framework for guiding the transformation of industrial system to a sustainable basis (Lowe and Evans, 1995). Saavedra et al. (2018), considers industrial ecology as a study that identifies the circulation of material and energy flows. For this reason,

industrial ecology must understand how the industrial ecosystem works, how it is regulated and its interactions with the biosphere.

Material and Energy Flow Analysis (MEFA) is a tool derived from industrial metabolism; this tool explores the stocks and material flows in a system (Taulo and Sebitosi, 2016), and also the energy flows. It is used mainly for ecology economics (Gerber and Scheidel, 2018), but it was used in different studies to understand the internal behaviour of industrial activities, for example in the canning industry (Bello Bugallo et al., 2012; Taboada Gómez et al., 2016). MEFA have been also defined as useful tools in the framework of Life Cycle Thinking (LCT), since it allows the knowledge of the flows (both qualitatively and quantitatively) in any part or the complete life cycle. Being LCT a philosophy that appears from Sustainable Development (Taboada Gómez et al., 2016), this focus can be used to define more sustainable systems. MEFA is proved by Cristobal Andrade (2012) to be a suitable tool for Improvable flows (IF) identification. In this context, IF are defined as quantitatively (or even qualitatively) relevant flows in an industrial system, which can be improved if properly managed (Torres Rodríguez et al., 2011). Flow identification tools are used to detect some specific flows whose both qualitative and quantitative properties make them likely to be enhanced by implementing techniques from the inventories (Cristobal Andrade, 2012).

Best Available Techniques (BAT) Analysis, as proposed by Barros et al. (2007b), evaluates techniques candidate to be BAT following the method set by the EIPPCB (European IPPC Bureau). The Directive 2010/75/UE on Industrial Emissions (Integrated Pollution Prevention and Control) defines the concept BAT as a reference to establish emission limit values (EU, 2010a). BAT must be continuously updated and the update must include the last technical improvements and developments (Torres Lopez et al., 2017), as it appears in the BAT Reference Documents or BREFs. This method was first proposed and validated in a ceramic industrial ecosystem (Barros et al., 2007b), to facilitate the implementation and evaluation of the techniques candidate to be BAT under the principles of the Integrated Pollution Prevention and Control (IPPC) philosophy. Since then, this approach it was applied to other industrial systems with the same aim, i.e., evaluate the BAT candidates for an industrial system (Barros et al., 2008; Barros et al., 2009a; Giner-Santoja et al., 2012; Cikankowitz and Laforest, 2013; Ibañez-Forés et al., 2013; Bello Bugallo et al., 2014; Yukeseler et al., 2017; Evrad et al., 2018). Moreover, it was also used combined with quantitative evaluation tools (such as MEFA, Exergy Analysis, Process Simulation) with the aim to define methodologies to obtain more sustainable configurations of industrial systems (Torres Rodríguez et al., 2011; Cristobal Andrade et al., 2014; Taboada Gómez et al., 2016). BAT analysis is used also with the aim to evaluate the environmental behaviour of plants from the same industrial sector (Bello Bugallo et al., 2012; Torres Lopez et al., 2017).

The aim of this chapter was to investigate and validate methodologies for the identification of more sustainable operating configurations for a tuna purse seiner. The proposed methodology is based on those detailed above and applied only for the moment to punctual industrial systems, due to the origin of the IPPC focus was developed in the EU for the most potentially industrial polluting sources. The idea is to apply the same methodologies and concepts used for the secondary industrial punctual sources, to a mobile activity from the primary industry. Based on the work by Torres Rodríguez et al. (2011) developed for a ceramic industrial installation, the proposed and applied methodology in this chapter combines BAT Analysis with MEFA.

The marine fishing activity is analysed under the scope of industrial ecology, taking into account in this case the proper fishing activity from a LCT vision (from the harbour to the harbour). The base case configuration, the typical activity from harbour to harbour in a purse seiner, will be analysed from both a qualitative and a quantitative point of view. The material

and energy flows (inputs and outputs to and from each identified stage) will be analysed by MEFA analysis tools. This analysis allows to identify IF in the system from a sustainable point of view, as well as more sustainable configurations of conventional purse seiner activity using tools based on pollution prevention, a control focus and the circular economy prospective, in this case through BAT Analysis.

6.2. METHODOLOGY

In this chapter a methodology for the identification of more sustainable mobile ecosystems is proposed and validated. This methodology, based on another one previously proposed (Torres Rodríguez et al., 2011) and applied to different stationary industrial systems, will be proposed, adapted and applied for the first time to a mobile industrial system, a tuna purse seiner. The methodology used in this chapter was previously validated in punctual industrial activities (Barros et al., 2007b; Barros et al., 2008; Bello Bugallo et al., 2012; Torres Rodríguez et al., 2011). This methodology combines two tools: MEFA and BAT analysis, providing a way to detect IF and selecting sustainable options to improve them. The methodology involves a qualitative analysis, including the collection of information from technical sources, an exhaustive description of the system, an analysis of the environmental aspects and a BAT analysis. MEFA adapts the methodology proposed by Hendriks et al. (2000), whereas BAT Analysis uses the method adopted from the EIPPCB by Barros et al. (2007b).

The methodology used includes the following steps:

1. Case study definition. In this part a selection of a purse seiner ship will be determined by contacting to the different enterprises, and based on criteria previously identified.
2. Qualitative analysis. This point includes the identification of the limits of the case study, description its stages, inputs and outputs, including the environmental aspects. This analysis is based on technical visits, bibliographic review, and interviews with experts in the sector.
3. Quantitative analysis. The quantitative analysis includes the quantification of the material and energy flows specified in the qualitative analysis. For that a MEFA software tool will be selected and used. This tool needs to be feed with data from the case study. The steps included in this quantitative analysis are the following:
 - a. Data acquisition: identification of the data needed for the quantitative analysis related to the stages and flows considered in the qualitative analysis. The acquisition of the data related to the case study will be by direct information (measurements, reports, interviews, visits, etc.) from the enterprise, specific data from reports and journals related to the case study, scientific studies, etc. Most data are calculated or estimated (especially the outputs), and the related information is obtained from databases related to emission inventories, environmental protection agencies, etc.
 - b. Scenario modelling. This step includes the following:
 - i. Software selection to develop the MEFA.
 - ii. System modelling using the selected software. This part includes the input of the data, the simulation, the calibration, and the results compilation.
4. IF Selection. The results obtained from MEFA are analysed to identify the IF, i.e., the remarkable flows to be sustainably improved (from a quantitative or qualitative point of view) in comparison with the other flows of the process.
5. BAT Analysis.
 - a. Inventory of the techniques candidate to be BAT for the selected system.

- b. Identification of the already implemented BAT in the case study.
- c. BAT selection according to IF. Candidate techniques to be BAT are selected for each of the identified IF.

6.3. APPLICATION OF THE METHODOLOGY

In this section, the methodology previously proposed is applied step by step to the tuna purse seiner, including the selection of the specific case study.

6.3.1. Case study definition

Ocean is in decline, and fishing activity is one of the most important anthropogenic marine activities. Therefore, it is important analyse to the fishing sector and reduce overfishing, and especially marine pollution and go towards sustainable industrial ecosystems. The case study is a mobile system, a tuna purse seiner, selected due to its significant economic impact and as source of food. Purse seiner is the fishing gear with most tuna catches (Figure 6.1). Although the case study selected is very specific, this approach can be used to with other ships and fisheries with similar characteristics.

The selected ship is the 'Draco' (Figure 6.2), built by Freire Shipyard in Vigo (Pontevedra, Spain) (IP, 2006). Draco is 95.7 m in length and has 2550 m³ capacity tanks, with the necessary means to purse seine fishing using a system highly mechanized and a crew of 30 people. This purse seiner is dedicated to tuna fishing in the West and Central Pacific Ocean zone to be exact, lasting two months (IP, 2006). The selection of Draco as the case study for this chapter was due to data availability, as a more complete dataset was obtained.



Figure 6.2. Draco (Infomarine, 2006)

6.3.2. Qualitative analysis

This analysis consists on a description of the case study, including four stages whose objective is tuna fishing, and the identification of the main environmental aspects linked to the fishing activity. This analysis is based on technical visits, bibliographic review, and interviews with experts in the sector.

6.3.2.1. Description of the case study

This part includes the identification of the limits of the case study, the definition and description of its stages. This analysis was carried out through technical visits, specific documentation of the case study as well as bibliographic review. Purse seine fishing process has four consecutive stages whose objective is the capture of tuna and its transport from the fisheries location to port.

The stages of the system have been identified as shown in Figure 6.3, the flow diagram elaborated to facilitate the development of the following points of the methodology. The identified stages are:

1. Initial operations. They are carried out when the ship is moored at port. These operations consist in the load of all the necessary materials for the machinery: fuel, oil, brine, new ammonia, spare parts and Fish Aggregating Devices (FAD); as well as the preparation of the engine. These activities mainly generate exhaust gases and noise from the engines, hydrocarbons pollution, residues and toxic waste (old spare parts, bilge water, oil, batteries and ammonia) from maintenance operations.
2. Processing. The processing stage starts when the ship leaves the port to arrive to the fishing ground. When the ship is in the fishing ground, searches a school of fish using electronic devices and looking over from the crow's nest. When the school of fish is found, the ship initiates the approximation manoeuvring. When it is in a correct place, the barge is launched, the purse seine is made and tuna is caught. Tuna is trapped manoeuvring the ship, the barge and with the help of speedboats. Later, purse seine is closed and the catch can be got on board using a grab net which loads up to 10 ton of fish per time (ICCAT, 2008). After the fish is on board, it is lead to the storage tank via a conveyor belt or channels where tuna can be inspected and rejected if it is necessary before its storage in the tank (Delgado, 2010). Later, fish is frozen using seawater and brine as refrigerating fluid, which is continuously cooled in a refrigeration plant with ammonia as thermal fluid. When fish is frozen, brine is pumped out of the tank, and disposed or reused in another tank.
3. Final operations. After several days of work, storage tanks are full and fish is completely frozen. In this moment, ship sets course to port where it will be emptied. Unloading operations can take several days, because fish is selected one by one. Main input in this stage is fuel, while outputs are exhausted gases, noise and hydrocarbons.
4. Auxiliary operations. Auxiliary operations are those that belong in the fishing activity, such as life on board, on high sea and moored at port also (cooking, cleaning, infirmary), auxiliary machines (electrical generation, hydraulic generation, auxiliary propulsion) and the needed for the normal running of several machinery, equipment and installations (winches, electronic devices, refrigeration system) and secondly auxiliary machines (desalination, fuel filtering, wastewater treatment, bilge separation) used to make easier the life on board and protect the equipment. These operations consume fuel, oil, and spare parts, cleaning products, provisions and fresh water. The outputs of this stage are: exhaust gases, hydrocarbons, noise, old parts, wastewater, sludge and urban residues.

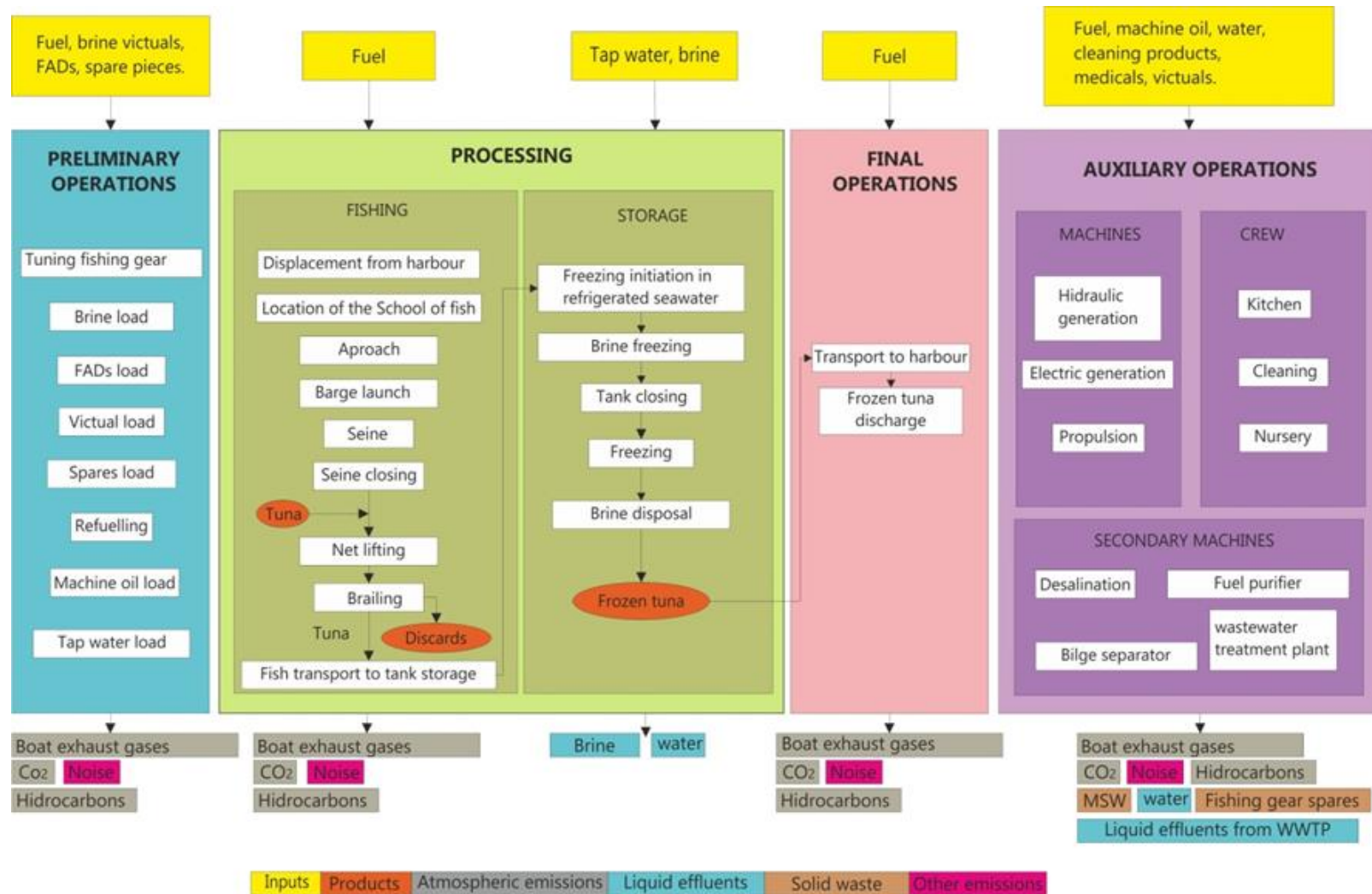


Figure 6.3. Flowchart and environmental aspects of the process

6.3.2.2. Environmental aspects

The main environmental aspects linked to the fishing activity can be classified in direct and indirect effects.

The direct effects include the fishing mortality on the populations of organisms targeted by the fisheries, the fishing mortality sustained by non-target organisms (bycatch and discards) and the physical impacts caused by the gear on benthic organisms and on the seabed.

1. Direct effects on target species (overfishing). These effects are produced when fishing optimum levels are exceeded owing to an increase in fishing effort, causing a proportional decrease in the global level of biomass, so that the renewal rate of the population is too small to assume the losses generated by the fishing activity, leading to the collapse of the fishery (UCA, 2015); summarizing, it is considered a reduction in biomass below some critical level such that the remaining fish are not able to replenish the population (Beamish et al., 2006). To avoid overfishing, irreversible, slowly reversible or long-term impacts, limit reference points are established, below which it is considered undesirable for a stock to fall (Nakatsuka et al., 2017).
2. Bycatch. Incidental fishing or discards that are then return to the sea. This fact raises a social issue over waste, representing a threat to the long-term capacity to provide food and a source of livelihood (Gilman, 2011). In the case of purse seiner, the incidental fishing is almost non-existent. However, the tuna purse seiner in the Central-eastern Pacific, where fishermen set their seines around groups of dolphins congregated over tuna schools, generates high dolphin mortalities (Goñi, 1998), although there are also incidental captures of sea turtles, marine birds, marine mammals, sharks, fish juveniles and non-tradable fish species (Gilman, 2011).
3. Physical impacts caused by the gear. Fishing activity has, in a lot of cases, a direct physical impact that can have a destructive effect. The most studied effect is derived of trawl benthic nets or trawl seabed nets (UCA, 2015), but in the case of tuna purse seiner, this effect is not relevant.

The indirect effects include impacts produced by biological interactions with the species in the ecosystem, the environmental effects of dumping discards and organic detritus and the effects of floating objects (Goñi, 1998; ICCAT, 2008).

1. Biological interactions between species in the ecosystem. The fishing activity can affect to the food chain; and interactions of competition and predation can replace the dominant species and substitute them (Goñi, 1998).
2. Environmental effects of dumping discards and organic detritus. The organic material discarded may cause changes in the structure and diversity of the marine communities, encouraging the proliferation of carrion and detritus feeding species (Goñi, 1998; ICCAT, 2008).
3. Effects caused by lost gear. There are evidences suggesting that floating objects affect the dynamic and structure of tuna schools, affecting their feeding ecology and possibly acting as a barrier to natural movements and migrations. These effects appear to be more intense in young populations and in small size specimen populations as vulnerability and catch rates of juvenile stocks increase, which will affect the very structure of the population and its reproductive potential (ICCAT, 2008).

Among benthic litter, a particularly relevant category includes derelict fishing gears. These benthic nets tend to remain entangled on the rocks, as well as on habitat structuring species (e.g., corals, sponges, bryozoans). Additionally, to the mechanical damage to benthic fauna, they still function for very long times and are able to catch

and trap fish and other organisms, so that these abandoned gears cause the called ghost fishing (Cau et al., 2017).

4. Pollution. Pollution, commonly refers to ‘the environmental damage caused by wastes discharged into the sea’, or ‘the occurrence of wastes in the sea’, or ‘the wastes themselves’ (Clark, 2002). There are different categories of pollution, such as air pollution, water pollution and soil pollution. Regarding emissions from international shipping, the most relevant concepts are marine pollution and air pollution (Shi, 2016).

In 2012, it was estimated that international maritime transport had generated approximately 2.2% of global carbon dioxide (CO₂) emissions (IMO, 2015). Therefore, it can consider that fishing large ships can be contributed to these emissions. Others pollution impacts are the problems with waste (plastics for example) and water discharges produced by ballast water (IMO, 2015).

6.3.3. Quantitative analysis: MEFA

The MEFA is applied to the proper fishing activity (from the harbour to the harbour), specifically to the stages identified in the qualitative analysis and shown in Figure 6.3. This analysis includes the quantification of the material and energy flows in the limits of the system and for each stage specified in the qualitative analysis. For that, a MEFA software tool will be selected and used to obtain the quantitative information of the flows.

6.3.3.1. Data acquisition

The necessary data to develop the MEFA have been both directly obtained or calculated/estimated from another available data, and information about the specific flow or stock (stage). Most of the data were obtained from the Draco shipbuilding installation, but also from articles in scientific papers as well as some other technical interviews.

As explained in the case study identification, the Draco is 95.7 m in length and has 2550 m³ capacity tanks. Its capacities, power and speed are shown in Table 6.2 (IP, 2006). Table 6.3 shows the average time of the main manoeuvres of a tuna purse seiner (ICCAT, 2008).

Table 6.2. Capacities, power and speed of the selected ship

Fish wells capacity	2,593.5 m ³	Main engine	6,000.0 kW
Fuel capacity in permanent	685.5 m ³	Speed	18.0 knots
Fresh water tanks	74.5 m ³	Main generating sets	3 x 1,020.0 kW
Lube oil tanks	99.5 m ³	Shaft generator	1 x 1,200.0 kW
Freezing capacity	200.0 tons/day	Bow thrusters	2 x 331.0 kW
Last freezer (-55°C)	5.0 tons/day	Stern thruster	1 x 441.0 kW

Table 6.3. Average length of the main manoeuvres of a tuna purse seiner (ICCAT, 2008)

MANEUVER	TIME
Establishment of the purse seine	2-4 minutes
Close of the seine	20-30 minutes
Establishment of the seine	1-2 hours
Brailing	1-2 hours (depends on the amount)

6.3.3.1.1. Fuel inlet.

To get the amount of fuel in kg that the Draco needs, we use data provided by the manufacturer. The Draco possesses three auxiliary engines (1005 kW), and one main engine (6000 kW) and the consumptions of each engine depend on the engine power (CAT, 2015; Mak, 2012) (Table 6.4).

Table 6.4. Engines and its consumptions (CAT, 2013; Mak, 2012)

POWER	CONSUMPTION
Main engine: 6,000 kW	178 g/kW-h to 100%
	177 g/kW-h to 85%
	179 g/kW-h to 75%
	189 g/kW-h to 50%
Auxiliary engine: 1,005 kW	207 g/kW-h to 100%

With the data provided by the manufacturer, the percentage of power used in each stage (Table 6.5) and the average time of each manoeuvre, the fuel used can be estimated (Martinez Caminero and Valera Marcos, 2007).

Table 6.5. Power percentage used in each stage (Martinez Caminero et al., 2007)

STAGE	MAIN GEAR	AUXILIARY GEAR
Consumption to the fishery	90%	95%
Consumption fishing and frozen	35%	87%
Consumption to the return and frozen	90%	84%

Concerning working time, a ship with the characteristics of the Draco, works approximately 277 days per year, and takes on average 6 days to arrive to the fishery (Tyedners and Parker, 2012). Regarding fishing manoeuvres (Table 6.3), an average of the time that the Draco needs for each manoeuvre and its stages can be obtained. For one manoeuvre, the time is 3 h, and knowing that 619 is the average of manoeuvres in one year estimated from bibliographic data (Delgado de Molina et al., 2012), it obtains that the Draco works 1859 h per year. With these data and knowing that main engine works at 35% and auxiliary engines at 87% with the Table 6.4, it can estimate 1,769,163 kg of fuel per year only for fishing.

In order to calculate in kg, the fuel inlet while the ship approaches to the fishery, it is known that the main engine works at 90% of power and one of the three auxiliary engines at 95% of power (Table 6.5). The main engine at 90% of power produces 5400 kW, with a consumption of 178 g/kW-h (Table 6.4). Also, the main engine consumes 916,200 g of fuel in one hour, knowing that ship travels 6 days to arrive and it leaves 3 times in one year, so the fuel consumption is 415,238 kg per year. One auxiliary gear working at 95% has a consumption of 85,535 kg per year. Secondly, the ship uses auxiliary engines at 84% when it returns to port for keep freezing, so, looking Table 6.4 and Table 6.5, and knowing that the time is 18 days per year it is estimated that the consumption is 226,582 kg per year for the auxiliary engines. Main engine, to return, consumes 415,238 kg per year, the same to go, so the total consumption to return is 641,814 kg of fuel per year. Table 6.6 shows a summary of fuel input data.

Table 6.6. Fuel input data

Consumption fuel	Going to the fishery	Fishing and frozen	Return and frozen
Main engine	415,238.0 kg	757,596.6 kg	415,238.0 kg
Auxiliary engine	85,535.0 kg	1,011,566.9 kg	226,582.0 kg

6.3.3.1.2. Oil input.

Draco has capacity for 99.5 m³ of oil (IP, 2006), and the total consumption of one departure is 65% (Martinez Caminero and Valera Marcos, 2007). Knowing that each departure Draco lasts approximately 90 days and the average of days per year are 277; Three departures per year are considering (by estimation).

The main engine has a consumption of oil of 0.6 g/kW-h, estimated from the manufacturer (Mak, 2012). Therefore, considering 18 days of one-way displacement per year with a 90% of engine power, the input of oil is 1399.7 kg/year. The auxiliary engine has a consumption of 0.1 g/kW-h (Mak, 2012), and the estimation is 41.26 kg/year of oil. For the return (18 days again), the main engine has the same consumption, 1399.7 kg per year. But in back-way to port the 3 auxiliary engines work at 84% of power to keep the freezing, besides the increase in the weight due to the fishing, and this oil consumption is estimated 109.4 kg per year. During fishing, the main engine works at 35% and the three auxiliary engines work at 87% to freeze tuna and keep it frozen. Therefore, it is estimated that the consumption of oil for the main engine during 1859 h of fishing per year is 2339.82 kg per year. On the other side, similarly, it is estimated that the consumption is 487 kg of oil per year for the auxiliary engine. Data of oil inputs can be observed in Table 6.7.

Table 6.7. Oil input data

Consumption oil	Going to the fishery	Fishing and frozen	Return and frozen
Main engine	1,399.70 kg	2,339.82 kg	1,399.70 kg
Auxiliary engine	41.26 kg	487.00 kg	109.40 kg

6.3.3.1.3. Emissions

The air emissions are the most relevant losses, and the most problematic, having even international conventions for the pollution as MARPOL (IMO, 2002).

The main emissions result from combustion, and they are CO, COV, NO_x, CO₂ and SO_x (Trozzi and De Lauretis, 2009). At the European level, the most important pollutants are SO₂ and NO_x, controlled by MARPOL (IMO, 2002). Pollutants are calculated by emission factors for each one, relating the amount of pollutant with the quantity of burned fuel. As the tonnes of fuel are known, the total emission of each compound is easily calculated.

In the Table 6.8 the most important pollutants with its emission factors and its units can be seen (Trozzi, 2010).

Table 6.8. Pollutants with its emission factors and its units (Trozzi, 2010)

POLLUTANT	EMISSION FACTOR	UNITS
NO _x	63.10	kg/t fuel
NMVOC	2.40	kg/t fuel
TSP PM10, PM2.5	1.50	kg/t fuel
CO	7.40	kg/t fuel
SO _x	0.30	kg/t fuel
Pb	0.13	kg/t fuel

POLLUTANT	EMISSION FACTOR	UNITS
Cd	0.01	kg/t fuel
Hg	0.03	kg/t fuel
As	0.04	kg/t fuel
Cr	0.05	kg/t fuel
Cu	0.88	kg/t fuel
Ni	1.00	kg/t fuel
Se	0.10	kg/t fuel
Zn	1.20	kg/t fuel
PCDD/F	0.13	t _{EQ} mg/t fuel
HCB	0.08	kg/t fuel
PCB	0.38	kg/t fuel

6.3.3.2. Scenario modelling

6.3.3.2.1. Software selection

The selected software used to build the model is Umberto® Version 5.0, which allows modelling, calculating and visualizing material and energy flow systems. Material and Energy Flow networks in Umberto consist of three different types of elements (IFU, 2005).

1. Transitions: represented by squares; these are sites in the flow network where materials and energy are transformed.
2. Places: represented by circles, these are locations in the flow network where material and energy are stored or distributed. There are three different types of places (inputs, outputs and connections).
3. Arrows: these elements link places and transitions. They show the direction of materials and energy flows.

6.3.3.2.2. System modelling.

The system was modelled using two different non-linear networks: the first one modelling the displacement from port to fishery and it is represented by two transitions (main engine and auxiliary engine) and the second one representing the fishing activity (considering all its stages), storage and freezing. All transitions were specified through mass and energy balances to define the relation between input and output. The main network for this case study is shown in Figure 6.4.

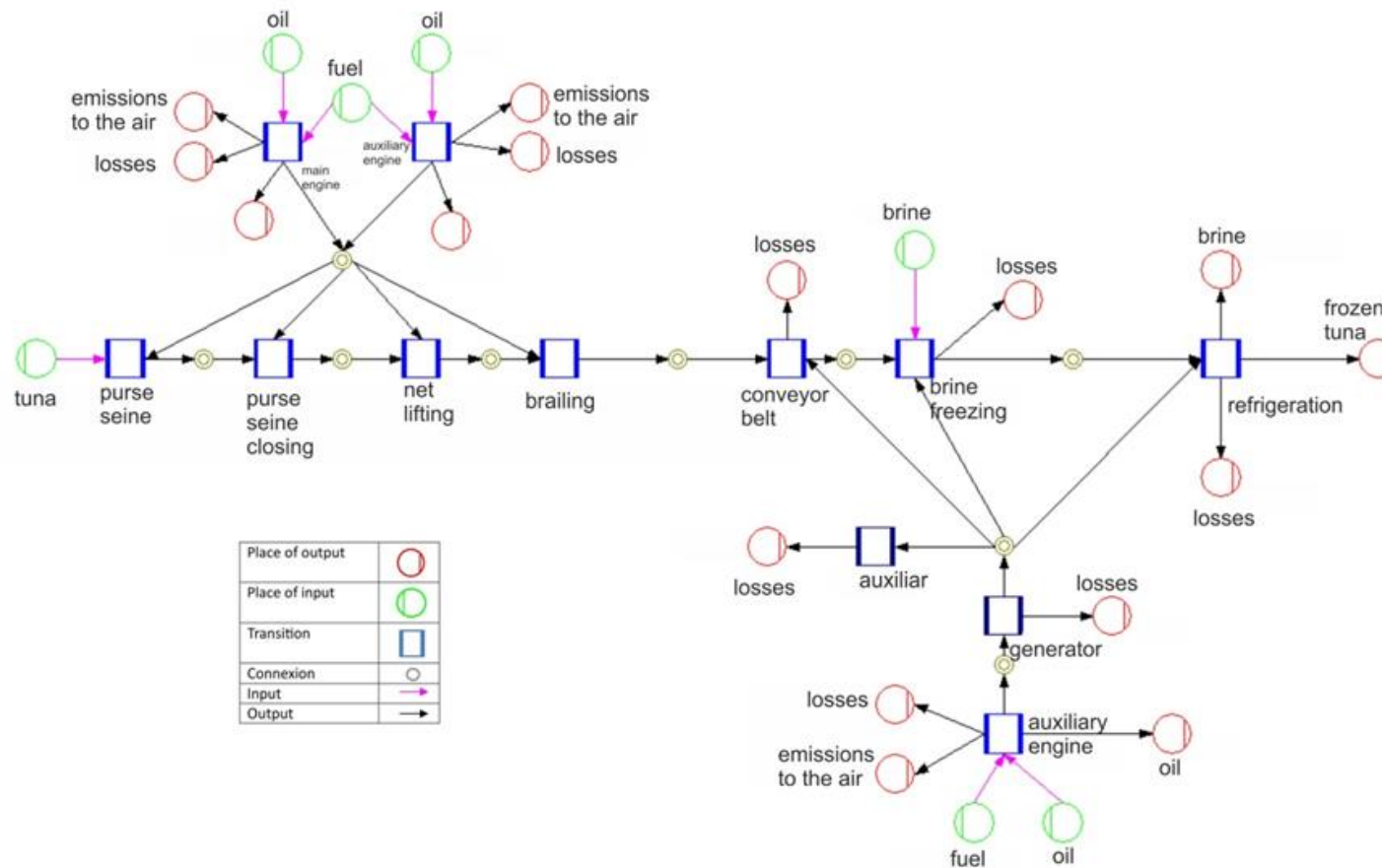


Figure 6.4. Main network

Running the model in Umberto, material and energy flows calculated by simulation, can be visualized using Sankey diagrams. These diagrams show the width of the arrows, which are proportional to the flow quantity. Figure 6.5 shows the most relevant Sankey diagrams for both networks.

In the displacement from port to fishery, the fuel consumption in the main engine is greater (415,238.40 kg/yr.) than in the auxiliary engine (85,535.10 kg/yr.). These results were estimated from the data presented in data acquisition. Moreover, the main engine needs more quantity of machine oil per year (1399.68 kg/yr.) in comparison with the auxiliary engine (41.26 kg/yr.). In the Sankey diagram representing work and losses, it can be seen that to greater power, the losses are higher; as in any thermal engine. Concerning emissions, the main pollutant in both engines is the NO_x , followed by CO, NMVOC, particles and SO_x . In the scenario representing fishing activity, storage and freezing, a new flow appears. It is the fished tuna, which needs brine to be frozen. In this case, the consumption of the auxiliary engine is greater than in the main engine, unlike in the previous scenario. However, the fuel consumption in the main engine during the fishing stage is greater than the fuel consumption in the same engine during the displacement stage. Regarding work and losses, the higher work consumption stage is the freezing process. As in the previous scenario, the main pollutant in both engines is the NO_x , followed by CO, NMVOC, particles and SO_x .

6.3.4. IF selection

From the results from MEFA and viewing the Sankey Diagrams (Figure 6.5), five IF have been identified in the process, shown in Table 6.9.

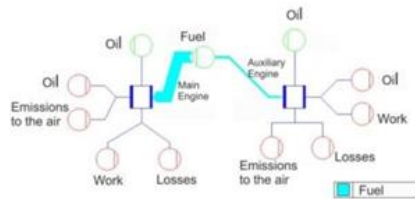
Table 6.9. Improvable flows identified for the process

Scenario	Stage	IF inputs	IF outputs
Displacement to fishery	Main engine	Fuel	Emissions to the air
Fishing activity, storage and freezing	Auxiliary engine	Fuel	Emissions to the air
	Brine freezing	Brine	-

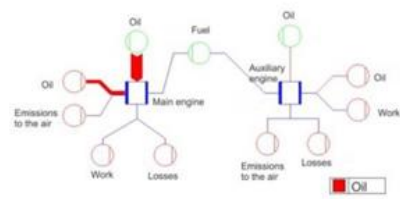
Sankey Diagrams show that, in the stage “Displacement from port to fishery”, the “fuel consumption” and “air emissions” are IF, due to their high consumption of fuel and pollutants emissions to the air. During the “fishing” stage the IF are the “brine consumption”, by the large amount of brine used for freezing. Moreover, “fuel consumption” and “air emissions” of the “auxiliary engine” are the additional IF in the fishery stage.

Displacement from port to fishery

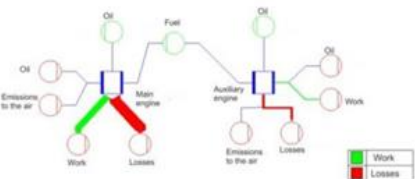
Fuel Consumption



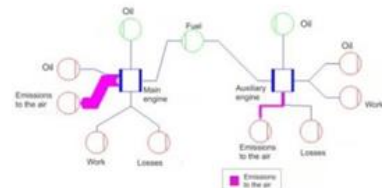
Oil Consumption



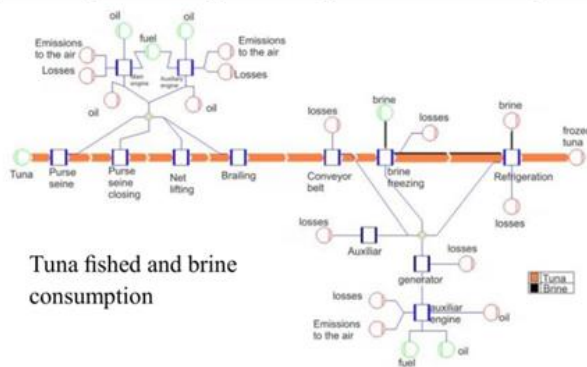
Work and Losses



Emissions

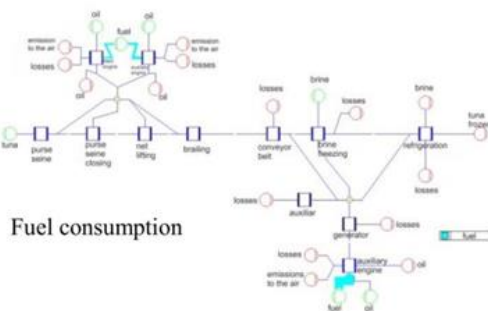


Fishing activity, storage and freezing

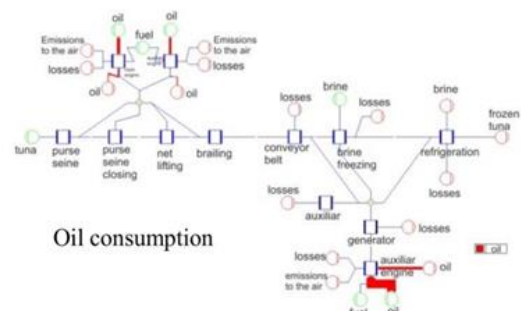


Tuna fished and brine consumption

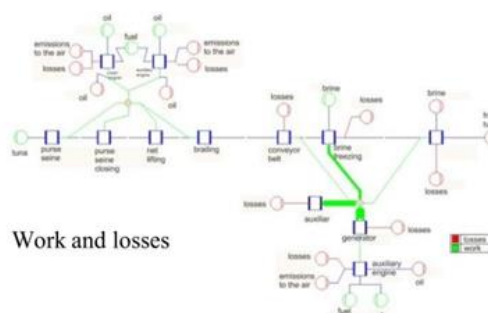
Place of output	
Place of input	
Transition	



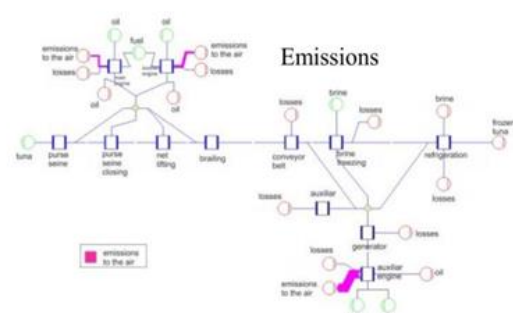
Fuel consumption



Oil consumption



Work and losses



Emissions

Figure 6.5. Sankey diagrams obtained for the process

6.3.6. BAT analysis

6.3.6.1. Inventory of techniques candidate to be BAT

It is the first time that the methodology developed by Barros et al. (2007b) is applied to a mobile system, a tuna purse seiner. Following this methodology, a technical data sheet (see Figure 6.6, Figure 6.7, Figure 6.8 and Figure 6.9) has been implemented for each technique candidate to be BAT for this type of systems, including: description, technical description, achieved environmental benefits, environmental performance and operation data, cross media effects, technical considerations relevant to applicability, economics, driving force to implementation and example plants. Finally, an inventory of thirty-one techniques candidates to be BAT for any purse seiner is developed (Table 6.10), applied then to the case study.

6.3.6.2. Identification of already implemented BAT

The tuna purse seiner addressed in the present study has already implemented twenty-four BATs (ticked in Table 6.10) of thirty one available in the inventory. In this way, it is legitimate to say that the degree of implementation is already quite high.

Table 6.10. BAT inventory

Technique	Implementation
Apply frequency controllers on motors	✓
Apply thermal insulation, e.g., of pipes, vessels and equipment used to carry, store or treat	✓
Avoid keeping air conditioned and refrigerated areas colder than necessary	✓
Cleaning of the hull	
Cogeneration	
Collaboration with upstream and downstream activities	✓
Condensers pressure optimisation	
Correct waste management	
Equipment and installation cleaning	✓
Fit silencers at air inlets and exhausts, to reduce noise levels	✓
Keep the condensers clean	✓
Make sure that the air entering the condensers is as cold as possible	✓
Minimise emissions to air	✓
Minimise motor losses	✓
Minimise the loads of motors	✓
Minimise transmission and ventilation losses from cooled rooms and freezers	✓
Only pump up the quantities of water that are actually required	✓
Operate centrifuges to minimise the discharge of product in the waste stream	✓
Operate without automatic defrosting during short production stops	✓
Optimise the air inlet temperature	✓
Optimise the condensation pressure	✓
Optimise the condensation temperature	✓
Periodic defrosting	
Prevent emissions of substances that deplete the ozone layer	✓
Regularly defrost the entire system	✓
Review the pressure level and reduce it if possible	✓
Stop equipment when it is not being in use	✓
Thermal isolation increasing	

Technique	Implementation
Use automatic defrosting of cooling evaporators	✓
Use of low nitrogen content fuel	
Use variable speed drives to reduce the load on fans and pumps	✓

6.3.6.3. BAT selection according to IF

Some candidate techniques to be BAT are proposed for those IF identified from the MEFA (Table 6.9):

1. Main engine (displacement to fishery). To reduce both the IF ‘fuel’ and ‘air emissions’ the collaboration with upstream and downstream activities to avoid long distance displacements is proposed. Also, the use of low nitrogen content fuel (such as Liquefied Natural Gas-LNG) can reduce the NO_x emissions to the air and therefore, the IF ‘air emissions’. In Figure 6.6, it is shown a proposed technical data sheet for this candidate BAT. Three more techniques are also proposed (Figure 6.7, Figure 6.8 and Figure 6.9): cleaning of the hull for fuel saving, correct waste management and cogeneration.
2. Auxiliary engine (fishing activity, storage and freezing). The techniques proposed to improve both the IF ‘fuel’ and ‘air emissions’ are the optimization of the condensers pressure, periodic defrosting, increasing the thermal isolation, only pump up the quantities of water that are actually required and use of low nitrogen content fuel.

Brine freezing. The IF ‘brine’ cannot be further improved, as there is no BAT in the inventory that can improve it, and it has the expected value for such a process

USE OF LOW NITROGEN CONTENT FUEL	
DESCRIPTION	Burning of Liquefied Natural Gas in main engine (IMO, 2015).
TECHNICAL DESCRIPTION	The LNG is stored in liquid state. It is driven to an engine or turbine which produces the mechanical energy to move the ship. It reduces hugely the emissions of NO _x , SO _x , CO ₂ and particulate matter compared to fuel engines due to a less content of S and C.
ACHIEVED ENVIRONMENTAL BENEFITS	Reduces the emissions to the air: NO _x , SO _x , PM and CO ₂ .
ENVIRONMENTAL PERFORMANCE AND OPERATIONAL DATA	It reduces the emissions to the air: NO _x , SO _x , PM and CO ₂ . NO _x is reduced 85%, CO ₂ 25% (Really 15%, due to CH ₄ increase) and nearly zero SO _x (IMO, 2015; NVG, 2015).
CROSS MEDIA EFFECTS	It increases the methane emissions, so the real depletion in the CO ₂ emissions is 15%. The risk of accident increases because it is a newer technology and the LNG is stored under high pressure (NVG, 2015). An accident could produce the violent release of a big quantity of gas to the atmosphere.
TECHNICAL CONSIDERATIONS RELEVANT TO APPLICABILITY	The installation requires high amounts of space, so it is difficult the implantation in a fishing ship (NVG, 2015). It is being installed in bigger vessels where space is not a problem. The price of the LNG is less than distillate fuels. The technical development is only starting and there are few engines in the market and all of them are medium speed four stroke engines. Currently the main solution is the dual-engine ship, which can burn gas, diesel or combination of both. The lack of bunkering LNG in harbours is also slowing down the development of this technology in ships.
	
ECONOMICS	The installation is more expensive than fuelled ones. The price of the LNG is cheaper than distilled fuels (the price of LNG is the same than residual fuel oil).
DRIVING FORCE TO IMPLEMENTATION	MAROPOL Tier III zones.
EXAMPLE PLANTS	Ferry (Business Green, 2015).

Figure 6.6. Technical data sheet for a candidate BAT: Use of Low Nitrogen content fuel

CLEANING OF THE HULL FOR FUEL SAVING	
DESCRIPTION	Cleaning of the hull for fuel saving
TECHNICAL DESCRIPTION	A proper cleaning of the hull and propeller can save fuel due to a less hydrodynamic resistance. A more effective hull coating can reduce the number of dry-docking for cleaning operations or other maintenance systems (diving, robot) (IMO, 2015, SEAWARDMARINE, 2015). 
ACHIEVED ENVIRONMENTAL BENEFITS	The resistance to flow is reduced, which means fuel savings and lower emissions to atmosphere
ENVIRONMENTAL PERFORMANCE AND OPERATIONAL DATA	Fuel savings can reach 5% (IMO, 2015)
CROSS MEDIA EFFECTS	New coating means emissions to atmosphere (VOC) and industrial wastes due to abrasion and cleaning operations. Operations in shipyard increase the noise level and particulate emissions. Cleanings underwater means emissions to water due to coating and paint particles and rust in addition to algae and barnacles release.
TECHNICAL CONSIDERATIONS RELEVANT TO APPLICABILITY	The technique can be applied in every ship. The larger the ship is, the bigger the savings are
DRIVING FORCE TO IMPLEMENTATION	Harbours have specific rules about works underwater
EXAMPLE PLANTS	It should be general maintenance in all ships

Figure 6.7. Technical data sheet for a candidate BAT: Cleaning of the hull for fuel saving

CORRECT WASTE MANAGEMENT	
DESCRIPTION	Correct waste management, with a good waste classification, storage in specialized containers and treatment according to waste quantity and type with the purpose of recycling.
TECHNICAL DESCRIPTION	Management containers (NORTIM, 2015) are designed to reduce the volume of wastes in ships via special treatments. The recovery of wastes allows future recycling in times of incineration on board without energy recovery (IMO, 1997). Urban waste can be classified and correctly treated (cooled storage, can crusher, rubbish press, classification, etc). 
ACHIEVED ENVIRONMENTAL BENEFITS	Increase of recycling activity (in port). Reduction of air emissions and fuel consumption (IMO, 1997). According to IMO Garbage Plan (IMO, 2012). Reduction of discharges on water.
ENVIRONMENTAL PERFORMANCE AND OPERATIONAL DATA	It could reduce emissions to air and fuel consumption due to garbage incineration nearly to 100%. It needs an electric energy inlet. The volume of wastes is decreased up to 80%.
CROSS MEDIA EFFECTS	It consumes electric energy which implies fuel consumption. Garbage storage could produce odours due to putrefaction of organics so cooled storage is needed. The cooled storage increases the electric energy consumption and a refrigerant fluid takes part increasing noise level.
TECHNICAL CONSIDERATIONS RELEVANT TO APPLICABILITY	The modular system allows totally customized equipment according to waste type and people on board. It can be easily loaded on board and unloaded so an installation out of order can be rapidly substituted. The major obstacle is the space occupied by the container or the machinery. Several equipment is used (crusher, compactor, refrigeration system...) meanwhile other solutions involve only several containers or a unique machine (IMO, 1997). So a wide space on the deck or under deck is forced.
DRIVING FORCE TO IMPLEMENTATION	MARPOL.
EXAMPLE PLANTS	Leif Hoegh ASA.

Figure 6.8. Technical data sheet for a candidate BAT: Correct waste management

COGENERATION
DESCRIPTION
Increase the energy efficiency by the exhaust gases energy recovery (IMO, 2015).
TECHNICAL DESCRIPTION
Waste heat from exhaust gases and engine can be recovered and used in a shaft generator/motor to generate electric energy or to assist the main engine (IMO, 2015; SIEMENS, 2010; SIEMENS, 2008).
The diagram illustrates a cogeneration system on a ship. It features a Main engine connected to a Power turbine and a Steam turbine. Exhaust gas boiler is connected to the Steam turbine. A Generator is connected to the Power turbine. The system is controlled by a Power Management System (PMS). The PMS is connected to Ship service power and Auxiliary engine. The diagram also shows a Ship service team and a Ship service power source.
ACHIEVED ENVIRONMENTAL BENEFITS
• Reduce the consumption of fuel and the GHG emissions • Additional power available without fuel consumption • General reduction in the main engine gas emissions • Reduction in water discharges from the main engine refrigeration system
ENVIRONMENTAL PERFORMANCE AND OPERATIONAL DATA
Reduces the consumption of fuel (12% less) and the GHG emissions (SIEMENS, 2010; WARTSILA, 2015) Decrease in the oil consumption (7% less) (WARTSILA, 2015) It is adequate to small and large engines. It can be implemented in used propulsion plants or in new equipment The recovered energy can be used to boost the main engine or to manoeuvre or low speed cruise
CROSS MEDIA EFFECTS
The weight of the ship is increased. The temperature of the exhaust gases is reduced so the dispersion of the emissions is lower. It generates noise.
TECHNICAL CONSIDERATIONS RELEVANT TO APPLICABILITY
Higher savings are reached with larger power plants. Smaller ships have less space for the installation and the investment is high.
ECONOMICS
The cost of an installation is 9.5 mill. \$ and it saves between 2.25 and 3.48 mill \$/year in a ship with a 80,000 kW newly built main engine which runs 6,500 h/year (WARTSILA, 2015) .
DRIVING FORCE TO IMPLEMENTATION
MARPOL GHG restrictions compliance.
EXAMPLE PLANTS
GUDRUN MAERSK (SIEMENS, 2010)

Figure 6.9. Technical data sheet for a candidate BAT: Cogeneration

6.5. RESULTS AND DISCUSSIONS

The main results of this chapter include the identification of the IF of the case study through MEFA, and selects candidates BAT from an inventory to improve those IF from a sustainable point of view.

After MEFA modelling applied to the case study, the Draco purse seiner, Sankey diagrams were generated (Figure 6.5), in which five IFs (Improvable Flows) were identified. Thicker coloured arrows represent these IFs. Four of them are related to the “fuel consumption of the auxiliary engines and main engine”, and the last identified IF is the result of “brine consumption”. The stage “Displacement to the fishery” has two IF related to “fuel consumption” and their respective “air emissions”. Otherwise, the stage “fishery” features three IF, named “fuel consumption” and “air emissions” in the “auxiliary engine” and “brine consumption” to tuna freeze.

After BAT analysis, valid to any purse seiner, an inventory of thirty-one detected BAT candidate techniques was obtained (Table 6.10). Twenty-four of these thirty-one candidate techniques are already implemented in the case study ship, indicating a high degree of BAT implementation. To act upon the identified IF, additionally to the implemented BAT, new candidates BAT from the inventory were selected for implementation to improve the behaviour of the case study from a sustainable point of view.

The easiest solution would be to find a closer fishing ground, and to reduce the size of the ship, so that the impact would be smaller. As this solution is not viable due to the need of space to catches, from the inventory of BAT developed, four isolated alternatives not yet implemented can be proposed:

1. Use of low nitrogen content fuel: it reduces emissions, although the problem lies in the installation of the engine, since it needs a larger boat size.
2. Cleaning of the hull: it decreases the cost of fuel is the cleaning of the helmet, which allows to eliminate water drag.
3. Correct waste management: Recycling on board the ship, besides eliminating and reducing waste, allows the possibility of incinerating on board if necessary, recovering energy.
4. Cogeneration: it allows generating energy; therefore, it reduces the fuel expense.

Available literature supports the techniques proposed to reduce fuel consumption and therefore the air emissions. Although measuring the impact of hull cleaning is difficult because there are other influential factors, such as velocity, wind direction, high waves and so on, is clear that it can improve energy efficiency (Adland et al., 2018). On the other hand, in an analysis of cogeneration system for ships, Tien et al. (2007) affirm that the cogeneration is an efficient, clean and reliable approach to generating power and thermal energy from a single fuel source. By recycling this waste heat, cogeneration plants achieve a dramatic improvement in the system's efficiency. In addition, the higher efficiencies of cogeneration reduce air emissions of nitrous oxides, sulphur dioxide, mercury, particulate matter and carbon dioxide, which are the leading greenhouse gases associated with climate change. Other technique, supporting by Jafarzadeh et al. (2017) is the use of Low Nitrogen Content Fuel (LNG) securing that powering fishing vessels with LNG may be a solution for reducing air emissions from the fleet. Finally, it is known, as said Harz and Davis (2002) that plastics, paper, cardboard and combustibles (representing 75 to 85% of a ship's total solid waste), including food waste, are incinerated at sea; to avoid incineration management containers have been designed recover to energy and reduce fuel consumption.

6.6. CONCLUSIONS

The aim of this chapter was to define more sustainable configurations of a tuna purse seiner. For this purpose, a methodology based on a previous one applied to date solely to sustainable industrial punctual systems, has been proposed for a mobile industrial system and validated in the Draco purse seiner, the selected case study. The criteria considered for the analysis were in the context of the Integrated Pollution Prevention and Control focus, developed in the EU for the most potentially industrial polluting sources, as well as both the industrial ecology and the Life Cycle Thinking approaches. In this context the used tools combined for the analysis of the system were: “Material and Energy Flow Analysis” (a tool derived from industrial metabolism, which looks the Improvable Flows), and “Best Available Techniques analysis” (a tool derived from the integrated pollution prevention and control focus). The “Material and Energy Flow Analysis” provides a way to detect “Improvable Flows” into the system, and the “Best Available Techniques analysis” provides a way to define sustainable options to improve those “Improvable Flows”. Applying the identified BAT to the IF, allows defining a more sustainable configuration of the tuna purse seiner.

The study of this system was difficult to simplify in a single model due to the non-linear consecutive processes. Several assumptions were made to get the system modelled in accordance with bibliography. There are important amounts of information about BAT in the food industry, but there is an evident lack of studies of this industry in mobile systems. The main environmental problems of this kind of ship are the elevated fuel consumption and the air emissions, especially NO_x . This is due to the big dimensions of the ships, the powerful engines needed to the long distances that they must cover between fishery and port, and the freezing power required to keep the product in a proper temperature.

From this chapter we can also deduce that large fisheries, in which ships have to travel long distances and remain for months in fishing grounds, would also have similar IF. In this way, the results presented in this study can be easily compared with vessels enrolled in fisheries that travel long distances. The practical application of the identified technologies to fishing systems will contribute to prevent and reduce marine pollution, great threat to the oceans. Finally, this methodology demonstrates to be a good tool not only towards sustainable punctual systems, but also towards sustainable mobile systems such as the fishing activity in oceans, as the tuna purse seiner validated here.

CHAPTER 7. SUSTAINABLE FISHING NETS

SUMMARY

Tuna purse seine fishing is one of the most important fisheries in the world. This fishery uses Fish Aggregating Devices (FADs), deploying 100,000 FADs a year and losing and abandoning many of them. Currently they are manufactured with plastic materials causing environmental impacts in the ocean. Regional Fisheries Organizations are trying to manage the large number of these devices deployed at sea, although this is an ongoing issue. Due to the importance of FADs in the sea, their great impacts and with the aim of finding solutions to the problem, a systematic review of the literature is carried out through the Spanish Foundation for Science and Technology (FECYT). The publications are grouped into eight categories where it is observed that, although most research focuses on animal behaviour, the most current topics are research in relation to the impacts caused and the management of these devices. Although the topic "Biodegradable networks" has turned out to be very little studied, it has been considered important as a solution to the impacts caused by FADs. Therefore, four possible types of biodegradable materials have been identified, highlighting PHB. These can be made from tropical fruit waste that generates large amounts of food waste. Therefore, an exhaustive investigation on the production of PHB from food waste would be the next step for this analysis, because of these would reduce the impact generated by waste both in the sea and in the food industry, contributing also to the circular economy.

7.1. INTRODUCTION

Fishing sector is of great economic importance worldwide, employing approximately 40 million people, with 4.6 million vessels worldwide (FAO, 2018). This data is considerable if we think on the amount of waste generate. Orasutthikul et al (2017) say that more than half of the waste dumped or lost directly in the seas, around 640,000 tons are networks of fishing. Nets can remain in the environment for long periods, because modern arts are mainly made of non-biodegradable synthetic fibbers (Baeta et al., 2009). The main materials used for fishing nets are a range of plastics including polypropylene, polyethylene, nylon, polyvinyl chloride, polyamide, and polystyrene (GESAMP, 2016). These non-degradable materials have become one of the most serious problems worldwide (Grimaldoa et al, 2018). For this reason, this topic has recently drawn the attention of science and authors such as Grimaldoa et al (2019), on the study of the effectiveness of biodegradable fibres with respect to non-biodegradable networks. Orasutthiku et al (2017), had taking into account that the fishing nets are mainly made of nylon (not biodegradable), they focus the research on the recycling of the fibbers.

According to the FAO, (2018) tuna fishing is one of the most important fisheries. It accounts for around 25% of landings in the central-western Pacific. In previous studies (García Rellán et al, 2018), the purse-seine gear (Figure 7.1) is described as the most important tuna fishing gear in terms of quantities.

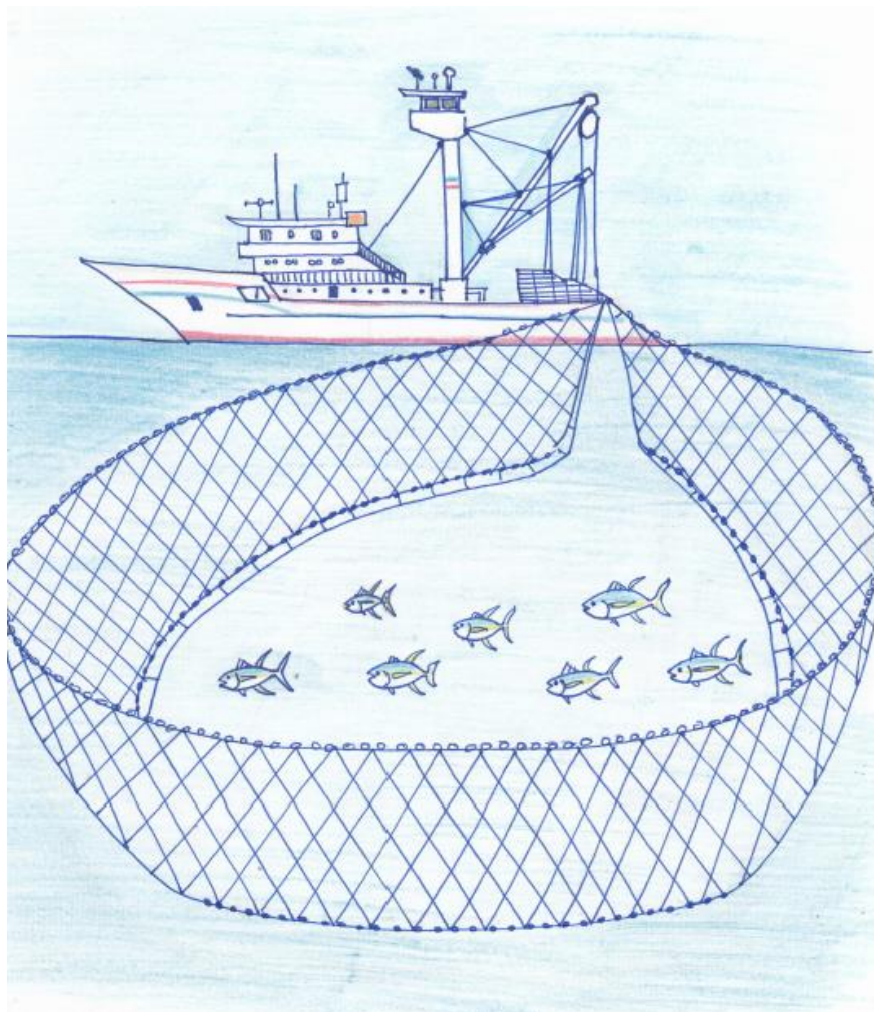


Figure 7.1. Purse Seine (Own elaboration)

Figure 7.2 shows an updated graph of the tuna quantities according to the fishing gear. As can be seen, the shape of the graph has not changed and the purse seine remains the most widely used fishing gear.

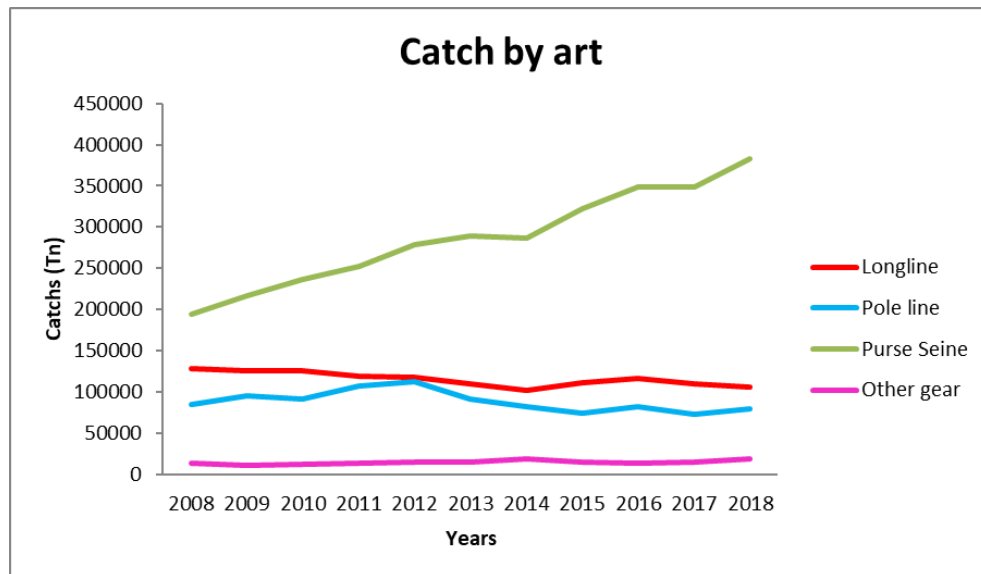


Figure 7.2. Tuna catches in ton with different fishing gears from 2013 to 2022 (ICCAT, 2020)

Since the beginning of the tropical tuna purse seine fishery, fishermen have taken advantage of the associative behaviour of tuna with floating objects. Although it was not until the 1980s that artificial FADs (Fishing Aggregating Devices) with radio buoys began to be built and deployed (Dupaix, 2024). These devices, which are used to attract fish (Tri Hargiyatno et al., 2018), increase the efficiency and profitability of the fishery (Griffiths et al., 2019). Most modern fleets use these devices to locate schools (Hanich et al., 2019), although they may also have to estimate tuna distributions and abundances to inform stock assessments (Boyra et al., 2018). A FAD is defined as any type of floating object that was modified by fishermen, monitored to track its trajectory (Lennert-Cody et al., 2018). Whether created naturally, like a floating log, artificially created by fishermen to add fish through habitat creation, FADs may be drifting or anchored (Hanich et al., 2019). The European Commission (EU, 2010b) classify FAD as anchored or drifting, and referring to the materials with those built:

- Anchored FAD: artificially moored to the seabed to prevent drift, including support damage anchored to an underwater mountain.
- Drifting FAD with net: not anchored and composed of a panel and associated with a net use as a sail in the sea.
- Drifting FAD without net: unanchored and composed of a panel, either continuous or in the form of a grid.
- Natural FADs: any FAD found at sea (for example, plant remains, dead animals, artificial debris) used as a FAD.
- Other drifting FAD: Any FAD other than the above

In a study of the evolution of FADs Hall and Román (2013) describe the most characteristic materials that make up these devices:

- PVC pipes (increase buoyancy)

- Sheets, sacks and plastic bags joined netting materials that are the basic elements of FAD (They increase their visibility)
- Most have nets hanging up to 30 m deep.
- Weight to maintain the device. The weight is almost 75% of the FAD weight (chains, cables, metal rings, etc. are usually used)
- Some of these FADs may include hanging bait.
- Currently it is common that they contain GPS location elements and devices that give information on the quantity of fish there is.

This study is based on the evolution until 2009, and the materials to be used are the most common. The DOUE, in 2017, publishes a Regulation that includes the requirements related to FAD in the area of the Convention of the International Commission for the Conservation of Atlantic Tuna (ICCAT).

These characteristics are:

- The surface structure of the FAD will not be covered by any material, or only with a material that represents a minimum risk of entanglement of by-catch species
- The components that are under the surface will exclusively contain material that does not cause entanglement of by-catch species.
- When designing FADs, priority will be given, if possible, to biodegradable materials, in order to phase out non-biodegradable FADs until 2018.

Because of the vulnerability of these devices to storm damage or anchor ropes being cut during adjacent fishing operations, FADs are frequently lost. They can also be deliberately abandoned in the oceans, in contravention of MARPOL Annex V (if made of synthetic materials) (Macfadyen, et al., 2011). These FADs lost contribute to the plastic, metallic and electronic waste in the marine environment. Furthermore, the ropes and nets that hang below the FADs can continue to entangle sharks and turtles (Thomas et al., 2019).

Currently, marine pollution through plastics is an emerging issue, and a worry worldwide, with many authors referring to this type of pollution (Van Wert et al., 2019; Ghayebzadeh et al., 2020; Kühn et al., 2020; Lyons et al., 2020; Capillo et al., 2020; Chubarenko et al., 2020). Plastics are now ubiquitous in the ocean, found in all oceans and on all coasts from the Arctic through the tropics to Antarctic (UNEP, 2016).

Demand for this type of material grows exponentially, according to the Plastics Europe report (2008), the production of plastic has grown from 1.5 million tons in 1950 to 245 million tons in 2006. But in more recent reports (Plastics Europe, 2023) the production of plastics in 2022 has risen to 400.3 million tons, with China being the main producer.

Regulation (EU) 2017/2107 (DOUE, 2017), says it is necessary to give priority when designing FADs, if possible, to biodegradable materials, in order to phase out until 2018 non-biodegradable FADs.

Biodegradable polymers can undergo degradation in small molecules like CO₂, CH₄ and H₂O due to the action of biota, generally microorganisms at a much faster rate than that of ordinary plastics. The ocean is not a disposal environment, therefore biodegradable plastics in the sea (which show complete biodegradability in a laboratory test method) could remain in ocean environments for very long periods of time and cause serious environmental impacts (GESAMP 2016).

Due to the importance of these devices, the objective of this chapter is a systematic review of the state of the art. All available bibliographic information is compiled and the most relevant study topics regarding FADs are presented. Once the most relevant information on these devices

has been collected, the biodegradable materials that best adapt to the characteristics of the FAD are compiled. With this recompilation is obtains biodegradable solutions which to manufacture FADs that are often abandoned in the sea.

7.2. METHODOLOGY

The methodology used in this project includes the following steps:

- Bibliographic search: The search is made using the Spanish Science and Technology Foundation (FECYT)
- Analysis of the bibliography: Each publication is read and analysed, the stages in which there are more publications are analysed, their origin and they are grouped by topic categories.
- Background and state of the art: each category of topic is analysed and the background and state of each of them are reviewed.
- Analysis of biodegradable materials: From the bibliography, the biodegradable materials that are most adapted for the construction of FADs are analysed. The material searched must adapt to the climatic conditions and the characteristics of these devices.

7.2.1. Bibliographic search

To verify the situation of the study system, a bibliographic search is made using the Spanish Science and Technology Foundation (FECYT), which manages the licenses of the two main world databases of bibliographic references and citations of publications, as a search resource periodic Web of Science, owned by Clarivate Analytics and Scopus, owned by Elsevier.

The review to this chapter was realized on April 2024 and 18 searches were carried out with the words "FAD"; "DFAD" (Drifting Fishing Aggregating Devices), "MFAD" (Moored Fishing Aggregating Devices), "Fishing", "Biodegradable", "Fishing Aggregating Devices", "Net", "DFAD", "MFAD", "Biodegradable net", "FOBs" and "Floating Objects" combined with each other. In addition, "Scholarships awarded", "editorial material", "corrections" and "patents" were removed from the filter. Table 7.1 shows the different combinations in the different fields and the number of results obtained in each one.

Table 7.1. Review

Number of search	Combination of words	Field	Number of publications
1	FAD	TITLE	105
	Fishing	TITLE	
2	FAD	TITLE	3
	Fishing	TITLE	
3	Biodegradable	TOPIC	6
	Fishing Aggregating Devices	TITLE	
4	FAD	TITLE	127
	Fishing Aggregating Devices	TOPIC	
5	Net	TITLE	24
	Biodegradable	TITLE	
6	FAD	TITLE	5
	Biodegradable	TITLE	
7	FAD	TITLE	24
	Net	TOPIC	
8	Biodegradable	TITLE	11
	FAD	TITLE	

Number of search	Combination of words	Field	Number of publications
9	Net	TOPIC	256
	Fishing Aggregating Devices	TOPIC	
	“FAD”	TOPIC	
	Fishing	TOPIC	
10	Fishing Aggregating Devices	TOPIC	51
	“FAD”	TITLE	
	Fishing	TOPIC	
11	Fishing Aggregating Devices	TOPIC	4
	DFAD	TITLE	
12	Fishing	TOPIC	2
	MFAD	TITLE	
13	Fishing	TOPIC	44
	“DFAD”	TOPIC	
14	Fishing	TOPIC	12
	“MFAD”	TOPIC	
15	Fishing	TOPIC	12
	“Biodegradable net”	TOPIC	
16	Fishing	TOPIC	5
	Biodegradable net	TOPIC	
	FAD	TOPIC	
17	“Biodegradable net”	TOPIC	17
18	FOBs	TOPIC	9
	Floating Objects	TOPIC	
	Fishing	TOPIC	

7.2.2. Analysis of the bibliography

After reviewing the articles and eliminating duplicates, a total of three hundred eighty-six articles remains. Of these three hundred eighty-six, there are thirty-nine publications that should be eliminated because they are not within the field of study. Therefore, there are three hundred forty-seven publications related to the searches carried out, but there are twelve without access. Finally, three hundred thirty-five publications are reviewed. Most of these publications are scientific articles published in journals. Only nine are doctoral thesis and thirty-three are proceedings. As seen in Figure 7.3, FADs are a very recent topic, most publications are concentrated in the last 10 years.

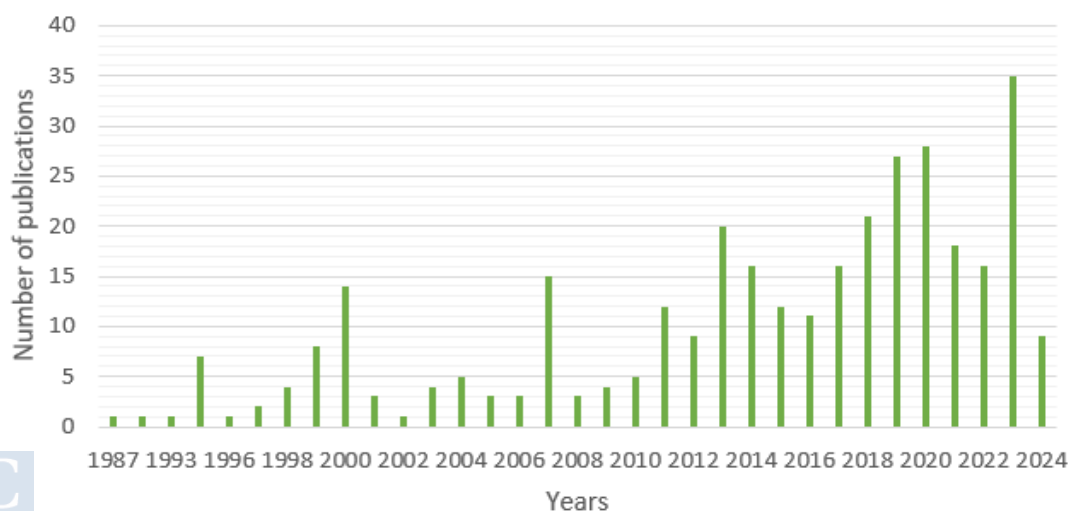


Figure 7.3. Publications per year

Once the three hundred thirty-five publications have been read, a classification is made by study topics. They have been grouped into seven study topics mainly and a group of "OTHER". The group "OTHER" are works that uses fish aggregation devices but the study topic is outside the field of fishing.

The categories are:

- **Nets:** Groups all publications related to the manufacture of biodegradable FADs and the search for biodegradable materials that can be used for the manufacture of FADs.
- **Biodiversity:** Groups those publications that study the biodiversity of the species around FADs.
- **Design:** refers to publications related to the design and characteristics of FADs.
- **Behaviour:** This category includes publications related to the study of the behaviour of different species around FADs.
- **Policy:** All publications that deal with the management of FADs in fisheries are included in policy.
- **Fishing with/without FADs:** They address studies related to the differences that exist between free school fishing (FSC) and fishing with FADs, or simply studies that look for differences between the two types of populations, free schools and those associated with FADs.
- **Impacts:** This group is related to research work on both environmental impacts and socioeconomic impacts such as food security.
- **Others:** this is a little group with studies that use FADs in them researches but they are not in the field of the study.

Figure 7.4 shows the categories and combinations between them. It is observed that the most studied category is the “behaviour of species around FADs” followed by the “Impacts” caused by these devices.

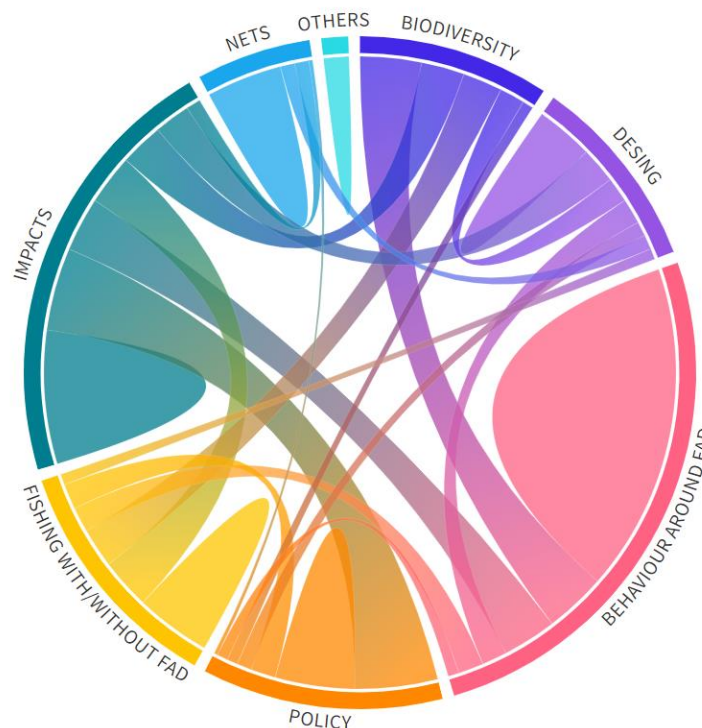


Figure 7.4. Topics and combinations about review

7.2.3. Background and state of the art

7.2.3.1. Biodiversity

The biodiversity category groups together fifty-seven works that study groups of species that are related to FADs, that is, those works that study the diversity of species around FADs. 35% of these studies are dedicated exclusively to this category, while 65% also include other categories. Furthermore, 26% of these articles are published in the last five years.

The first study in this category dates back to 1994, where the role of a large buoy in the high seas to attract and maintain fish communities in the Mediterranean was investigated (Relini et al., 1994). Later in 1999, Deudero et al (1999) recorded all the species that were added to the devices used as FADs, considering them as reproduction structures for many species. Most studies in this category are based on investigating and censusing the different animal species that are added to the FADs over time, building an ecosystem (Relini, 2000; Nelson, 2003; Andaloro, 2007; Taquet, 2007; Gaertner, 2008; Noranarttragoon et al, 2013; Takahashi et al, 2023; Schneider et al, 2023). Censuses were carried out in different seas or oceans, including investigating whether there are differences in fish aggregation using different types of FADs (Altinagac et al, 2010; Cillari et al, 2018) or differences in diversity using two types of fish nets fishing around the FAD (Sinopoli et al, 2012). Some works such as Folpp & Lowry (2006) study the abundance of fish around FADs in order to study and provide alternative fishing opportunities.

The most recent studies work with data obtained from FADs in tuna fisheries to estimate tuna biomass (Precioso et al, 2022). On the other hand, Baez et al (2022) review the data collection requirements obtained by FADs in tuna to create an appropriate standard data collection aimed at improving scientifically based information. Not only do the studies focus on fish, Hou, et al (2024) study the relationship of FADs with seabird dynamics in the Republic of Kiribati.

To a socioeconomic level these devices reduce fishing costs, and can protect reef and lagoon resources by transferring fishing effort to less sensitive species (Taquet 2013). In despite of this, the use of FADs can increase the risk of unsustainable stock status exacerbating the degradation of the fishing environment (Konoyima et al, 2024).

7.2.3.2. Characteristics / Desing

This category is made up of thirty-seven articles that try to address the design and characteristics of FADs. Most are dedicated to the study of these devices, although there is some work that shares categories.

Such has been the belief in the efficacy of FADs that investments have been dominated by practical issues of design and deployment (Albert et al, 2014).

The first work we found in this category dates back to 1994, which describes how FADs have evolved since their introduction in Hawaii (Higashi, 1994). Currently the FADs are made up of a raft, with a submerged panel and a beacon. Specifically, the rafts of French ships are made of bamboo, mesh and plastic (Reyes et al, 2022).

Although not many works have been found on the topic, according to Escalle et al (2023) fleets have used materials and construction approaches similar in recent years. To describe and classify them, the classification of Dempster & Taquet, (2004), in their review, has been used:

- FADs anchored
 - Heavy. A large buoy made of steel, PVC, foam filled tire, drums or fiberglass. They are usually moored with a single line anchored to one or three concrete blocks.
 - Semi-heavy. Many smaller pressure resistant buoys, moored in the same way as previous one. They tend to last longer.
 - Light. They are made with recycled materials from recovered buoys, or cheap materials such as bamboo, coconut leaves, palm or cork floats. They are the most used because they are cheaper and are built directly by the fishermen themselves.
- Drifting FADs. There is very little information on this type of FADs, most of it is found in documents related to purse seine fishing and they are made up of a raft, usually made of bamboo, equipped with radiolocation beacons, satellite buoys and sometimes with fish remote sensing devices. Large purse seiners use more than 100 of these devices per year. Furthermore, Moreno et al, (2024), assures that these must have a slow drift and create shadow for better attraction of fish.

In 2011, Shainee & Leira investigated the causes of the premature loss of FADs in the Ocean, analysing each part of these devices: Floating section, anchoring section, mooring section, and attracting section. There is also research on the interactions of wave forces and currents or wind in different materials for FADs (Ozgul et al, 2011) to try to improve the characteristics of them. Ghazali et al, in 2013, investigated the noise emanated by FADs, comparing two designs to observe the importance of noise in attracting fish. The most recent works are already beginning to investigate different biodegradable materials and with different designs that can be used in FADs (Lopez et al, 2019). They also investigate the current situation, structural design, fishing and ecological characteristics of these fish attraction devices in collaboration with tuna purse seine captains (Wang et al, 2020). On the other hand, Sinopoli et al (2020), evaluate the waste derived from these devices by analysing materials and designs of the FADs. These materials are usually plastic bottles, cork sheets, tire inner tubes and polystyrene sheets, plastic sheets, polyethylene, sisal or nylon cables and ropes and also palm leaves.

Regarding design, the hydrodynamic responses of 14 FAD designs are also analysed, in order to make a design more appropriate to the different climatic characteristics (Wan et al, 2022). And although there are works in which different designs are sought, it is known that the structure of the FADs may not play a key role in attracting fish. Current projects are designed to determine trajectory for example, such as Moreno et al (2023) who design a BioFAD inspired by jellyfish, structurally weak but still flowing smoothly with ocean currents. Although already in 2017, the Satlink company incorporated two probes that allow determining the biomass, the size of the grouped specimens and the composition by species (Bdi, 2017).

7.2.3.3. Behaviour around FADs

This category groups one hundred and thirty-three articles that try to understand the behaviour of fish around FADs. It is the most studied category. Understanding fish behaviour is a key element in scientific experience to help in population assessment and especially for fisheries management (Jauharee et al, 2021). Fish aggregation around floating objects has long been recognized and exploited by fishermen (Brehmer et al, 2019). The tuna purse seine fleet releases into the sea, for example in China, an average of 102 FADs per year per boat and an average of 72 are lost (Wan, 2020). The density of these devices at sea may be an important factor. Tolotti et al (2020) affirm that FAD density and biomass estimates will improve the interpretation of

residence and absence times of tunas (and other species) in FADs. This is studied in various articles how the density and distance between FADs affect the behaviour of tunas. For example, Damora et al (2020) studied how distance affects the movement pattern of tunas. Pérez et al (2020) states that when the distances between FADs are smaller, tunas visit more FADs, spend less time traveling between them and more time in aggregate. Travel between FADs may be due to their random search behaviour. Aggregation times may be the result of social behaviour and/or food availability. Taking advantage of this behaviour, Sinoppoli et al (2023), in their study, suggests that FADs could exert different effects on the distribution of juvenile fish. Offshore FADs retain fish for longer periods of time than coastal ones, and coastal FADs favour the transition of fish from the pelagic zone to the benthic zone.

Some of these works take advantage of the knowledge of fishermen such as Jauharee et al, (2021). They carry out a study based on interviews with fishermen in the Maldives. They suggest, for example, that strong currents are the main factor for the tunas to go to the FADs, although it is also believed that the high temperatures of the sea surface can be affect and stormy weather contribute to the departures. It is also believed that moderate currents are a favourable condition for forming aggregations in FADs, while other factors such as adequate temperature, dams and attractants enhance this aggregation.

On the other hand, technologies such as passive acoustic telemetry are used to describe the associative dynamics of the main tuna species (Tolotti et al, 2020, Filous et al 2020). Asai et al, (2021), develop an ultrasonic biotelemetry receiving system and a data communication terminal. Recordings made by an omnidirectional probe mounted on the hull of a ship, thus allowing the behavior of large schools to be monitored (Brehmer et al, 2019).

Although most studies are related to tuna fishing, one of the most current articles studies how these devices affect seabirds. This chapter confirms that these devices not only affect the behaviour of fish. Birds can change their behaviour by concentrating more in areas where there are FADs and observing a lower level of activity where there are no FADs (Hou et al, 2024).

7.2.3.4. Policy and management

This category is made up of fifty articles that address the management of FADs in the Ocean. It is a recent topic, 50% of the articles are published in the last 5 years.

There is a growing need to develop management measures that involve stakeholders from all sectors to ensure they are accepted and enforceable (Taquet, 2013). The management of these devices has become a concern for the different Regional Fisheries Management Organizations (RFMOs). These are in charge of managing the fishing of the different species of tuna in different places. Currently, the different RFMOs implemented and evaluated management measures such as (Morgan A., 2011):

1. Ban the FADs.
2. Restrict the number of manoeuvres on the FADs.
3. Restrict the number of FADs per boat.
4. Alternatives or design restrictions for FADs: For example, use of BioFADs (They must not entangle, do not use synthetic material or chemicals) (bdi, 2019).
5. School behaviour: Use of the behaviour of the school and take advantage of movements and actions to fish for the target species.
6. Restrict FAD depth.
7. Size limit in FADs.
8. Catch limit in FADs.
9. Control on ship efficiency.
10. Discard Ban.

11. Space-Time Ban.
12. Distance between FADs: Handayani et al, (2019) reconsider the location and distance of FADs in Indonesia so that fishing is not affected.

Although not all of these measures have been implemented and only in some RFMOs, management measures continue to be studied to avoid the impacts caused. Thus, Guillotreau et al (2023), study the possibility of implementing in French ships a reduction by half of the authorized FADs and without quota limit, a temporary ban on FADs with reallocation in free banks and without reallocation. But they ultimately conclude that the economic consequences would be detrimental to coastal states. Other authors, such as Holmes et al, (2019), say that temporary bans to limit impacts represent an imprecise management measure. This is due to can be easily avoid by moving the effort outside the ban Eka et al (2023), analyse the existing management to improve the location of FAD deployment in northern Gorontalo. On the other hand, the possibility of implementing a FAD management plan that optimizes the data collection system from the FADs to the RFMOs is being studied (Baez et al, 2022). Hanich et al, (2019) also propose three management actions: establish a centralized monitoring system for FADs, establish control over deployment to minimize losses, and have the Commission defines appropriate responses for FADs that arrive in a Zone Exclusive Economic (ZEE) without license.

Although fishing with FAD is a fact and the RFMOs take into account the impacts and each one implements its management measures, there are authors who question the legality of these devices. Churchill et al, (2021), analyse whether these devices break MARPOL standards and the marine pollution conventions. Abandonment could be considered “dumping.” Gómez et al (2020) also analyse its legality, since it could be considered illegal, unreported and/or unregulated (IUU) fishing.

In addition, there are certifications such as the MSC (Marine Stewardship Council) created by a non-profit organization that addresses the problem of unsustainable fishing that fishermen can join voluntarily (MSC, 2024). This type of certification can be effective in FAD management, as stated by Tolentino-Zondervan et al., (2018) evaluate the effect of MSC certification on both FADs and free schools.

7.2.3.5. Fisheries with and without FAD

In this category, fifty-one publications were grouped that address studies related to the differences that exist between Free School Fishing (FSC) and fishing with FADs, or simply studies that look for differences between the two types of populations, free schools and the associated to the FADs.

The use of these devices is technically more efficient than fishing in free schools. Although FSC fishing appears to consume less energy, FADs have higher success rates (Barsuko et al, 2022). Furthermore, if an echo-sounder is integrated into these, the effectiveness can increase by 2 to 2.5 tons more in the case of tuna (Wain et al, 2021). Konoyima et al (2024) observe the fishing types and evaluate the impacts caused by fishing with FADs and free schools. They show the state of overfishing with their models and demonstrate that fishing with FAD can increase the risk of an unsustainable stock. In the case of Skipjack tuna, fishing in FADs can increase the catch of small individuals and bycatch with respect to FSC fishing (Mallawa, A; 2020). The use of FADs is novel and has a high success rate. Due to, it can contribute to food security in many places. That is why there are some studies such as that of Eighani et al (2019), which compare fishing with FADs and free schools to quantify the potential of using FADs as a management tool. Even so, places like Kenya, fishing activities, although less efficient, are

carried out by artisans in small boats in shallow waters protected by the barrier reef (Onyango et al, 2021).

On the other hand, this group includes studies that compare the differences between free schools and schools added to FADs. For example, Ménard, et al, 2000, studies the possible differences in the diet of tuna associated with FADs and in free schools. The result is that FADs do not have a trophic function, but rather are a simple refuge. More recent studies are those by Ashida et al, (2017), which analyse the possibility of reproductive differences. In this case, the results suggest that the type of shoal does not affect spawning characteristics, but may affect oogenesis due to food availability. Other even more recent works indicate that skipjack tuna fishing in FADs tends to be located in areas with relatively higher levels of chlorophyll (Zainuddin et al, 2019).

7.2.3.6. Impacts

The “Impacts” category includes all publications that address in their objectives the impacts related to the use of FADs. This category is made up of ninety-five current publications, 66% belong to the last 4 years.

Worldwide, it is estimated that around 100,000 FADs are deployed each year (Murúa et al, 2023). Pons et al (2023) states that the majority of FADs are abandoned or lost, and between 7% and 22% end up stranded in coastal areas. This high density of devices in the sea each year can cause many impacts. Among the reviewed bibliography, different impacts caused by FADs are grouped:

1. Ghost Fishing: The abandonment or loss of FADs in the sea can affect the marine environment by entangling animals that pass near these devices (Pons et al 2023; Royer et al, 2023).
2. Bycatch: The dangerous impact of these devices in tropical and subtropical waters due to high levels of bycatch is known (Manfrini et al, 2023). These bycatches can be both juvenile individuals (Gómez et al, 2020), and key or vulnerable species such as the silky shark (*Carcharhinus falciformis*), which is one of the main elasmobranch species captured bycatch (Filmalter et al, 2021).
3. Danger to navigation: Manfrini et al (2023) indicate that FADs could pose a danger to navigation.
4. Marine pollution: Currently FADs are made with materials derived from plastic, metal and electronic components for tracking buoys (Murúa et al, 2023, Maufroy et al, 2018). A high number of these are lost or abandoned each year. Therefore, if poorly managed, they have the potential to contribute to marine pollution (Lovell, T.A., 2023).
5. Ecological trap. FADs could act as an ecological trap for species such as tuna. This is because it is a rapid, strong and long-lasting aggregation and can negatively affect the growth and natural mortality of juveniles (Marsac et al, 2000). That is, it suggests that fish can become trapped between groups of FADs, altering migratory routes and therefore affecting growth or reproduction (Morgan, A., 2011).
6. Economic impact: FADs are promoted around the world as tools to increase the income of fishermen and improve food security (Wilson et al, 2022).

The use of FADs can reduce search time and operational cost as they can be located quickly and report whether fish biomass is present. This improves performance and reduces fuel consumption (Granado et al, 2024). Therefore, increasing income.

7. Overfishing: overfishing can be a negative impact of the use of FADs (Morgan, A., 2011), especially if there is poor management of them (Wilson et al, 2022).

8. Habitat destruction: stranding of FADs can lead to the destruction of fragile habitats such as coral reefs (Maufroy et al, 2018).
9. Social impact: They can also fuel territorial disputes, leading to conflicts between fishermen (Valles. H. 2023; Wilson et al, 2022).

7.2.3.7. Biodegradable nets

This category groups twenty-seven publications after having eliminated 1 for referring to biodegradable nets for agriculture and not for fishing. Although it could be useful in the search for a biodegradable material, the environmental conditions to which it is exposed in the sea are much stronger.

This category includes articles that base their research on the search for a biodegradable material resistant to environmental conditions. Thiebaut-Rizzoni et al (2022) highlights the mechanical stress suffered by fishing nets and the use patterns mobilized by sailors during untangling of the catch. Although this material is not specifically for the construction of a FAD, it is for the construction of fishing gear due to the conditions it must support.

The construction of FADs is a very recent topic, and although we have grouped twenty-seven articles, only two are specifically related to the construction of FADs. Currently, the different RFMOs as a management measure are adopting the recommendations of the General Directorate of Maritime Affairs and Fisheries to gradually replace FADs with non-entangling FADs and promote research and use of biodegradable FADs (Zudaire et al, 2019; FAO, 2019).

Since 2010, several research projects have focused on designing and testing an FAD structure constructed primarily of biodegradable materials (Moreno et al, 2023). For example, BIOFAD, a European project coordinated by AZTI to test biodegradable materials in the constitution of FADs in the Indian Ocean. This project lasted from 2017 to 2019 and included the deployment of 1,000 biodegradable plants during 2018 (Azti, 2024).

Moreno et al (2023) propose a new concept of FAD which they call Jelly-FAD and imitates a jellyfish. This is made with biodegradable materials of vegetal origin such as recycled cotton and bamboo canes. Murúa et al (2023) analyse different vegetal fibres such as cotton, sisal, hemp and flax for rope construction and evaluate the potential for biodegradation, reproducibility and market availability. In this study the aggregation of fish in biodegradable FADs is similar to conventional ones, but the materials are not as resistant as conventional ones. Furthermore, the biggest drawback is the high price of materials.

As for materials that could be used to make FADs, they could be: PBS (poly (butylene succinate)), PBSAT (poly (butylene adipate-co-terephthalate)), PBAT (poly (butylene adipate-co-terephthalate)) or PLA (polylactic acid). It is known that PBSAT begins to degrade and weaken enough after two years of being in the sea to stop capturing fish (Grimaldo et al, 2018). Some authors such as Kim et al. al (2020), analyse the physical properties of fishing nets made with a mixture of PBS and PBAT resins through thermal processes. Later, Park et al (2023), use the resins as raw material to make fishing gear. of PBS and PBST, although drawbacks are found in both. PBS has low stiffness and elastic recovery and PBSAT has low tensile strength. All of these materials have been compared with conventional PA fishing nets. For example, Grimaldo et al (2018), states that PBSAT networks have the potential to be used as a viable alternative. An Heui-Chun (2013) compares conventional PA gillnets with PBS gillnets stating their efficiency. Finally, Yu et al, (2023) compare PLA nets with PA nets showing similar capture efficiency.

7.2.3.7.1. Biodegradable materials

Once the bibliography has been analysed, it is observed that some of the RFMOs are implementing as a measure the use of biodegradable materials for the construction of the FADs. Although the bibliographic review is already being implemented, only twenty-seven articles related to the adoption of a biodegradable material have been found. Because of this a search has been carried out for biodegradable materials that adapt to the peculiar characteristics that these devices have. In Figure you can see the set of biodegradable materials that can be adapted to the construction of FADs.

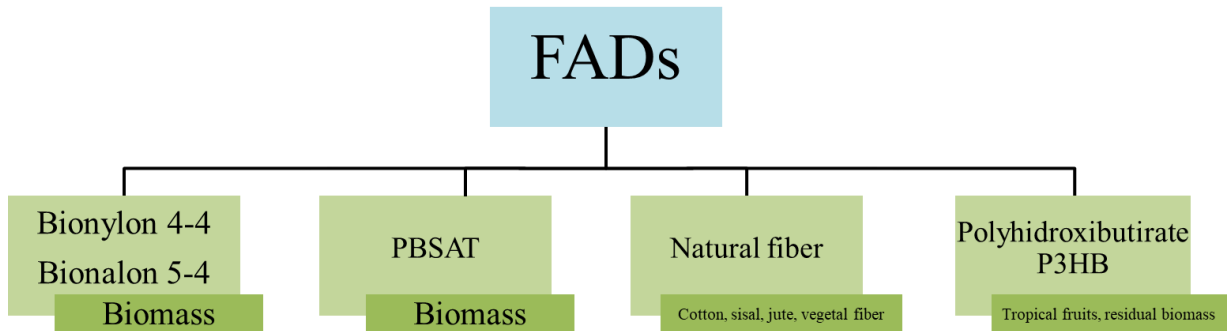


Figure 5. Biodegradable Materials for FADs

To replace conventional FADs, among others, the biodegradable materials that are best suited for the construction of Bio-FAD or biodegradable FADs are:

1. Natural Fibers: they are suitable materials for the construction of Bio-FADs compared to other biodegradable synthetic fibres due to their high availability and low cost. Compared with jute and sisal, experimental results show that twisted cotton yarns are the most robust with high breaking strength and maintain minimum durability in a saline environment (Lopez et al, 2019; Wang et al, 2020).
2. PBSAT (poly (butylene adipate-co-terephthalate)): This is a resin mixture of PBS (90% by weight) and PBAT (10%) by weight), which can be obtained from biomass. The problem with PBSAT in fishing nets is that its efficiency decreases as it degrades in a saline environment. Furthermore, its high manufacturing cost in relation to conventional materials is a big problem. (Tachibana et al, 2015; Torres et al, 2015; Grimaldo et al, 2020; Seonghun et al, 2020).
3. Bionaylon-4,4 and bionaylon-5,4: synthesized by a conventional condensation polymerization reaction of succinic acid (SA), 1,5-diaminopentane (1,5-DAP) and 1,4-diaminobutane (1,4-DAB) from biomass through the use of metabolically modified microorganisms. These biopolymers have almost similar physical and chemical properties to synthetic nylon 6,6, but more research will be needed to demonstrate their effectiveness in saline environments. (Lee et al, 2020).
4. PHB (Poli-3- hydroxybutyrate): It is a biopolymer of the PHA (polyhydroxyalkanoates) family. This shows very good adaptability and degradation properties in seawater. Furthermore, it is a material that could be synthesized by fermentation of a wide range of residual biomass included in tropical fruits such as pineapple with the help of appropriate microorganisms. (Silva et al, 2004; Sukruansuwan & Napathorn, 2018; Amini et al, 2020; Wang et al, 2021).

7.2.3.8. Others

This last group is a small group of seven publications that appear in the search and are outside the topic of study. Even so, they are grouped here because they actually refer to FADs in their studies.

They are publications that in their study method take advantage of the existence of FADs to evaluate, for example, oceanographic characteristics (Khan et al, 2020). In other publications, they install a turbine in the FADs to provide low-cost electrical energy to local communities without damaging the ocean ecosystem (Mutsuda et al, 2019).

7.3. RESULTS AND DISCUSSION

In this chapter, a systematic review of publications is made that focuses on Fish Aggregation Devices (FADs) due to their importance in fishing. A review is done using FECYT. To locate the publications, 12 keywords in 18 combinations were used, searched in both “title” and “topic”. A total of three hundred and thirty-five publications resulted after eliminating publications that went outside the object of study. Once all the publications were reviewed, they were classified into eight groups, which correspond to seven topics and one that join a small group that uses FADs in their work, therefore, they enter the search, but leave the object of study.

Although the first publications reviewed date from the late 1980s and early 1990s, it is a topic of current importance. More than 30% of the articles reviewed are published in the last 4 years. This is because these devices are mainly used by the tuna purse seine fleet, one of the most important fisheries in the world (FAO, 2018).

From the classification made, the “behavior of species around FADs” stands out as the most studied topic with one hundred and thirty-three publications. It is an important topic since FADs can, on the one hand, help understand the behavior of many species and also contribute to changing the behaviour of both fish and many birds (Tolotti et al, 2020; Hou et al, 2024).

On the other hand, in recent years, publications about the management of FADs and their impacts have been increasing. In the years 2023-2024, 25% of the publications address the management of FADs, and 31% the impacts caused by them. The management of FADs by RFMOs and the impacts caused are very current topics due to the number of FADs deployed around the world today. According to the literature found, these FADs are made of plastic materials and many of them are lost or abandoned. This fact can cause many impacts on marine ecosystems. These impacts are included in this document, as well as ghost fishing, habitat destruction or marine pollution.

Knowing that these devices are made with materials derived from plastics that contribute to marine pollution, this search has included keywords such as “Biodegradable”, “Fishing net” or “Biodegradable net”. Marine pollution is a worrying issue and is present in the management of these devices. Even so, twenty-seven articles have been found (55.5% in the last two years) for the classification of “biodegradable fishing nets”, and only two that are directly related to FADs.

The great problem of waste generated by FADs has attracted the attention of RFMOs that are beginning to implement the use of biodegradable materials. In the search for biodegradable networks in the bibliographic review, very few results have appeared investigating the topic. Due to this, different types of biodegradable materials that can adapt to the characteristics of FADs have been investigated. As a result, four types of materials are observed. The most promising materials were PHB and natural fibres such as cotton.

As for PHB, they are mainly produced from fruit and vegetable waste (Gowman et al., 2019). In this context, fruit residues and effective fermentation technologies play a crucial role

as a low-cost substrate for PHB production. Fruit waste in the form of peel, core, stem and crown, rich in fermentable sugars, can be used for the production of biopolymers (Gowman et al., 2019). A large amount of pineapple waste suitable for PHB production is produced in Asian countries such as the Philippines, Thailand, India, Indonesia and China. Furthermore, these wastes can become environmentally problematic due to environmental microbial deterioration (Roda et al., 2019), so the use of pineapple plantation residues for PHB manufacturing should be considered.

The remaining twenty-five articles deal mostly with the search for biodegradable materials that can be used in fishing gear.

7.4. CONCLUSIONS

The objective of this chapter is a systematic review of the state of the art. All available bibliographic information is compiled and the most relevant study topics regarding FADs are presented. Once the most relevant information on these devices has been collected, the biodegradable materials that best adapt to the characteristics of the FAD are compiled. With this recompilation is obtained biodegradable solutions which to manufacture FADs that are often abandoned in the sea.

Therefore, it is concluded that these devices (FADs) are of great importance for fishing due to the aggregation behavior of fish. Currently it is estimated that around 100,000 FADs are released per year (Murúa et al, 2023). Due to the high density of FADs in the ocean, their manufacturing materials and the fact that many are lost and abandoned, they can generate many environmental impacts. Among other impacts, stand out marine pollution, although the change in the behavior of many marine species could also be important.

On the one hand, a good common and international management for these devices would be a way to reduce not only the quantity of FADs in the sea, but also the waste generated by FADs. In this way, the impacts generated by FADs on different species and the waste generated would be reduced.

On the other hand, research into biodegradable materials resistant to the environmental conditions of the sea is of great importance for the manufacture of these devices. As has been seen, waste from tropical fruit plantations such as pineapple is a suitable alternative to produce PHB and can be used as fishing nets and FAD. For this, it is necessary to carry out more exhaustive research to make it more appropriate and profitable. This would be the second step to this investigation.

These biodegradable materials can help reduce waste from the food industry and the large amount of waste formed largely by fishing nets and FADs. In this way, waste becomes a safe and natural resource, contributing to the circular economy.

CHAPTER 8. SUSTAINABLE PRODUCTION OF MARINE EQUIPMENT IN A CIRCULAR ECONOMY: DEEPENING IN MATERIAL AND ENERGY FLOWS, BEST AVAILABLE TECHNIQUES AND TOXICOLOGICAL IMPACTS

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

Zapelloni, G.; García Rellán, A.; Bello Bugallo, P.M.; 2019. Sustainable production of marine equipment in a circular economy: deepening in material and energy flows, best available techniques and toxicological impacts. *Science of the Total Environment*. Vol 687; Pp. 991-1010. DOI: <https://doi.org/10.1016/j.scitotenv.2019.06.058>

- Title: Sustainable production of marine equipment in a circular economy: deepening in material and energy flows, best available techniques and toxicological
- Authors: Zapelloni, G.; García Rellán, A.; Bello Bugallo, P.M.
- Authors affiliation: Department of Chemical Engineering, Universidade de Santiago de Compostela, Av. Lope Gómez de Marzoa, s/n, E-15782 Santiago de Compostela, Spain
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SUMMARY

Nowadays a radical revolution in the production field is possible thanks to policies to fight against the environmental crisis and the technological progress, like Circular Economy.

Leisure activities at sea are anthropogenic activities that have a potential impact, not only on the marine environment in the use stage (e.g. microplastics) and the end-use stage (e.g. ocean plastic wastes), but also on the manufacturing stage of its life cycle. This last stage is also the most important to prevent and/or reduce the impacts by means, for example of eco-design.

This chapter aims to analyse the marine equipment manufacturing sector using fibre reinforced polymers (that potentially emits VOC with the consequently toxicological impact) from the circular economy prospective to identify sustainable solutions for the manufacturing process stage. The selected case study is a marine equipment job-shop using a Fibre Reinforced Polymers. A methodology to identify sustainable industrial systems previously validated is modified, adapted and applied to this case. The methodology applies three tools: Material and Energy Flow Analysis to identify the Improvable Flows of the process, Best Available Techniques analysis, to propose the most appropriate techniques to improve those improvable flows, and the Impact Analysis to evaluate and compare the effects on humans and ecosystems, on both the case study scenario and the improved ones.

Ten Improvable Flows have been identified for the process; consequently, fifteen candidates to Best Available Techniques have been proposed aiming to act upon these flows. The application of these techniques in an improved system, allows reducing the amount of material and emissions reducing the impact. The combination of those tools has confirmed to be a very good option for process evaluation considering sustainability criteria. The Impact Assessment has permitted to compare the base case scenario showing a reduction of the impacts by the selected Best Available Techniques.

8.1. INTRODUCTION

Circular Economy (CE) as an approach to combat environmental issues and promote sustainable development has recently received increasing attention in the discussions on industrial development (Prieto-Sandoval et al., 2018) being one of the most recent production philosophies (EC, 2015b, 2015c). This concept from the linear economic model of production “take, make, disposal” to the closed loop (in where raw technical materials may be recycled and reused, and the biological materials may turn back to the soil). A shift to a CE requires eco-innovations to close the loop of the products life cycle, get valuable products to others from waste and solve the needs of environmental resilience despite the tendency toward economic growth (Korhonen et al., 2018). Furthermore, it is necessary to innovate in policy, business models, financing and consumer behaviours (Whicher et al., 2018). Figure 8.1 adapted from Clark et al., 2016 describes the recirculation of resources for a specific product (in this case surfboards) taking into account the EU waste hierarchy but emphasizing the return to the use of materials incorporated in functional products.

Clark et al., 2016 say that circular economy increases the value of a material resource by maximising its conversion into products, and in doing so eliminating waste. This brings great economic benefits, contributing to innovation, growth and creation of employment. In 2015 the European Commission adopted an action plan to accelerate the transition to a CE. This action plan establishes 54 measures since production and consumption to waste management and the secondary raw materials market (EC, 2019b). In this sense, a best product design is essential to facilitate recycling and help make products that are easier to repair or more durable, therefore saving precious resources (EC, 2015b, 2015c). Then, the design of a product is identified as one of the main pillars of the European strategy of the circular economy (Vanegas et al., 2018). The design strategies in the EC are (Allwood and Cullen, 2012): to increase the efficiency of the material, to extend the life cycle and to improve the efficiency of recycling. For all this, technology plays a key role.

The design of a system in an integrated manner is considered as the most effective way to increase the productivity and reduce the negative environmental impacts of a system, as a product or a system, for example of engineering (Stasinopoulos et al., 2009). Eco-design was defined by Charter and Tischner (2001) as “sustainable solutions in products, services, hybrids or system changes that minimise negative and maximise positive in the field of sustainability through the life cycle of the products or existing solutions, satisfying social demands/needs”. In other words, the Eco-design is a concept which includes the human sustainable priorities along with business relations. The tools in eco-design are not as important as specifications, and their objective is based on the development of the product in its phases. Organizing the production development is crucial to achieve high levels of sustainability in early stages (Karlsson and Luttrupp, 2006).

Although there are many definitions, this concept deals the design in the sustainable develop context. Its objective is improving the environmental efficiency in the life cycle of the products, integrating environmental aspects in the first stage of the product design (EC, 2008b). In the products efficiency European policy context, eco-design legislation and energy labelling are going to contribute to reduce between 20 and 40% the energy goal to UE in 2020 (EC, 2016b).

Therefore, circular economy implies reducing waste to a minimum. When a product reaches the end of its useful life, its materials are used to make new products instead of being disposed. This implies that industrial symbiosis is important to promote innovative industrial processes. For example, industrial symbiosis allows waste or by-products of one industry to become inputs for another (EC, 2015b, 2015c).

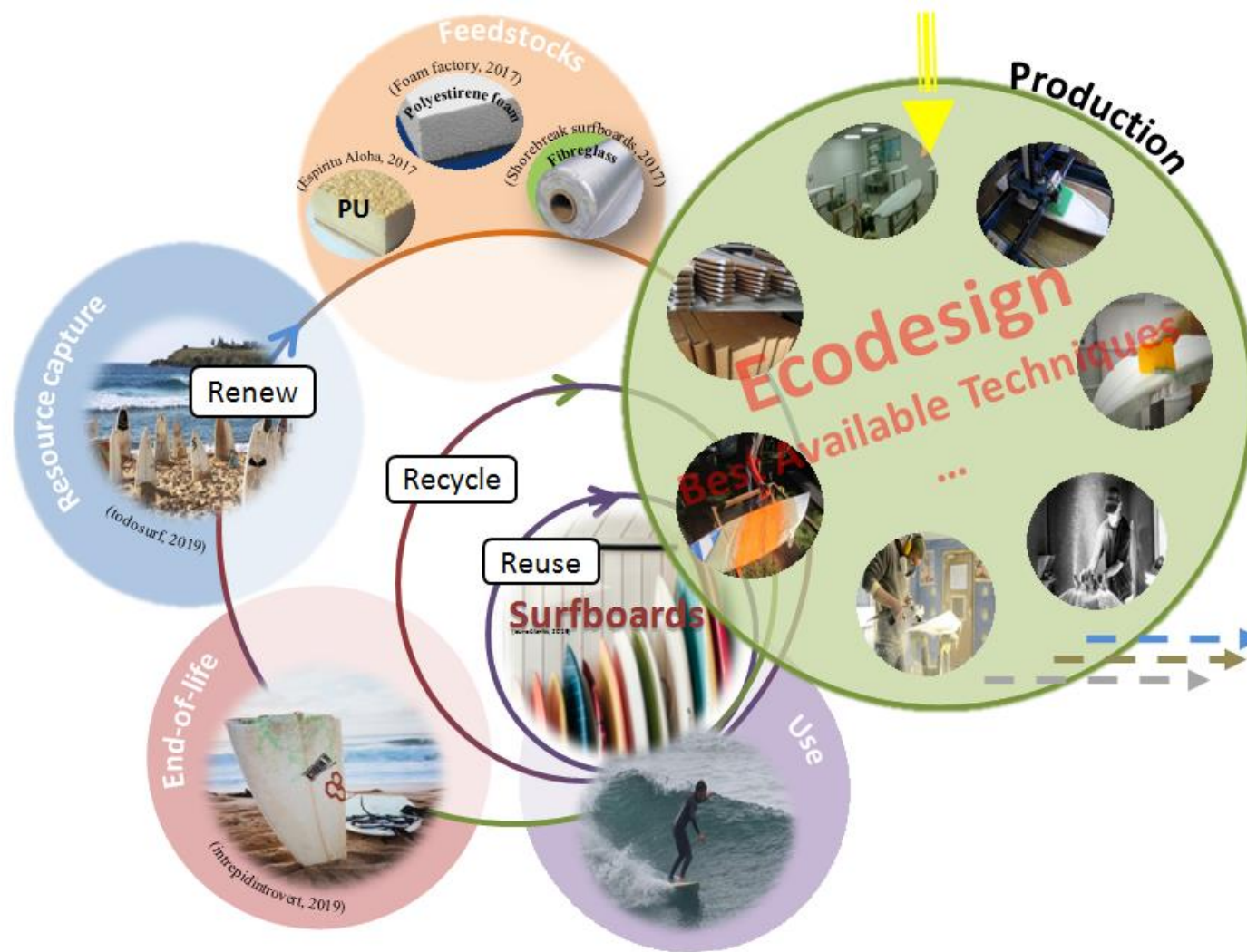


Figure 8.1. Circular economy (Adapted from Clark et al., 2016)

There are many examples of companies implementing the concept on specific products in various sectors (European Parliament, 2016). Each industry sector is different when it comes to resource use, waste generation and management. Therefore, the Commission will further promote best practices in a range of industrial sectors through the ‘best available technique reference documents’ (BREFs) (EC, 2015b, 2015c) which EU Member States must reflect when issuing permits for industrial installations (EC, 2017b). BREF documents began to be developed with the entry into force of Council Directive 96/61/CE, on integrated pollution prevention and control (MAPAMA, 2018), and now BREFs documents are in revision under the IPPC focus (Industrial Emissions Directive) (EU, 2010a). These documents referenced the Best Available Techniques (BAT). BATs are the most effective and available techniques, which include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned (EU, 2010a). The available techniques are “those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator” (EU, 2010a). Furthermore, BAT correspond to technologies and organizational measures that are most effective in achieving a high level of protection of the environment as a whole and can be implemented under economically and technically viable conditions (Huybrechts et al., 2018). Effectively the European Commission proposes to produce less waste by adopting a better waste management and resource efficiency practices, following the BREFs indications, for a more efficient use of resources (EC, 2015b, 2015c).

BAT analysis is a tool used in order to minimize Improvable Flows (IF) in a system (Taboada Gómez et al., 2016) and tested in many different examples (Laso et al., 2017; Yukeseler et al., 2017; Torres Lopez et al., 2017; Evrad et al., 2018, among others). In this context, IFs are those relevant flows in industrial systems, which can be improved if properly managed (Torres Rodríguez et al., 2011).

To detect Improvable Flows in a system Material and energy flow analysis (MEFA) can be used. This tool appears with the appearance of industrial ecology and the industrial metabolism concepts. Modelling material and energy flows is a good way to reach a high level of efficiency of a given process, through the effective use of resources and energy, or waste management (Czaplicka-Kolarz et al., 2014). The concept of MEFA is an approach of the interrelationship between the economy and the environment. In this relation, the economy is an embedded subsystem of the environment and dependent on the constant throughput of materials and energy (Taulo and Sebitosi, 2016). Flow identification tools are used to detect some specific flows whose both qualitative and quantitative properties make them likely to be enhanced by implementing techniques from the inventories (Cristobal Andrade, 2012).

In order to assess the environmental consequences of a product from cradle to grave the tool Impact Assessment (IA) was born (Dewulf et al., 2015). IA is a methodology to quantify and evaluate the magnitude and significance of the potential environmental impacts of a product system. Life cycle impact assessment (LCIA) is the method for converting inventory data from a life cycle assessment into a set of potential impacts (Laurin and Dhaliwal, 2017). LCIA, using Characterization Factors (CFs), translates elementary flows in terms of environmental impacts such as climate change, depletion of resources, acidification, ionizing radiation or human toxicity (Esnouf et al., 2018).

Marine equipment manufacturing is one of many industrial sectors that fall within the circular economy perspective, especially that one which uses polymers reinforced with fibre (commonly called Fibre Reinforced Polymer or FRP). Generally marine equipment production

such as ships, boats, canoes, surfboards, etc. use the same chemical polymers and materials (as raw materials) that can be harmful to the environment and human health. This is an industrial sector in which a lot of actions directed to strengthen the sustainable development through the incorporation of good practice and techniques of pollution prevention and reduction of health risks are possible. The most important environmental aspect of the sector activity is the presence and emission of Volatile Organic Compounds (VOC), especially the styrene, coming from the use of both resin and solvents. Particulate matter (PM) is also generated during the operations of shaping and glassing. Both VOCs and PM are hazardous for human and ecosystems (Tiger Foam, 2013; IEEP, 2018; Chandra et al., 2016).

The goal of this chapter is to develop, to apply and to validate a methodology focused in the Circular Economy to build a more sustainable production model in a marine equipment plant. To achieve this objective, three Life Cycle Thinking Tools are been used: Material and Energy Flow Analysis (MEFA), Best Available Techniques (BAT) analysis, and toxicological Impact Assessment (IA) on human beings and ecosystems. The intention is to search an improved process configuration and compare it with the conventional one. This is used shown how the combination of the previous tools turns out to be a good criterion of sustainability evaluation. In this chapter the emphasis will be for the production phase rather than for the use of the marine equipment product. The data and results of MEFA can be used in LCIA. Combining MEFA with IA is a good way to achieve a preliminary design for an eco-industrial configuration (Dewulf et al., 2015). The tool selected to study the impact on these two categories caused from the surfboard production is USEtox, a model launched by the Life Cycle Initiative (UNEP&SETAC, 2016).

8.2. METHODOLOGY

In this chapter a methodology to evaluate a sustainable production model in a marine equipment plant based on previous works (Torres Rodríguez et al., 2011; Taboada Gómez et al., 2016; Torres Lopez et al., 2017) was proposed. This methodology includes a new combination of tools to evaluate sustainability systems. It includes a Material and Energy Flow analysis (to identify the Improvable Flows of the process), the Best Available Techniques analysis (to propose the most appropriate techniques to improve those improvable flows), and Toxicological Impact Assessment Analysis on human beings and ecosystems (to evaluate and compare the effects on humans and ecosystems, on both the case study scenario and the improved one). The Figure 8.2 shown the methodology applied.

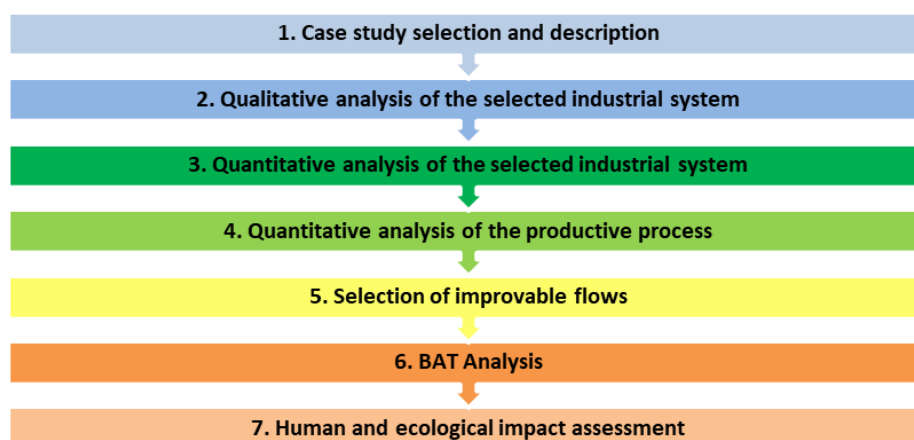


Figure 8.2. Methodology

- 1 Case study selection and description. This step includes the research of the Fibre Reinforced Plastic (FRP) equipment production plant in Spain and in Portugal. Some of the main factories in both countries have been selected and contacted. The final result of this step was the identification of the industrial plant to be considered as the case study.
- 2 Qualitative analysis of the selected industrial system. Identification of the system limits, definition and description of its stages, and analysis of inputs, outputs and internal flows. These analyses are based on technical visits to the plant and on bibliographic reviews.
- 3 Quantitative analysis of the production process. Data acquired during the visit of the plant are reported and explained. This step will be completed by a Material and Energy Flow Analysis of the system (MEFA). The steps are:
 - Data acquisition: identification of the data needed to fill the model. Data may be acquired by direct measurements at the industrial plant, best estimates, interviews, databases of environmental protection agencies and articles from scientific journals.
 - Model and scenario building. The network of the process is built, the model is run and MEFA results are obtained. This point includes the following steps:
 - Software selection.
 - System modelling using the selected software: scenario building creating networks and subnets. The model is fed with the data collected.
 - Model running and results of MEFA: when the model is completely implemented in the software, it is executed in order to obtain the results of the MEFA.
- 4 Selection of improvable flows. The results obtained from the MEFA are analysed to identify the Improvable Flows (IF). Sankey diagrams of the flows facilitate this task.
- 5 Best Available Techniques (BAT) Analysis.
 - Recompilation and inventory of the candidate techniques to be BAT in the selected system. The candidate techniques are inventoried according to the methods proposed in previous works (Taboada Gómez et al., 2016).
 - Proposal of alternatives to the process. Candidate techniques to be BAT are selected for each IF identified.
- 6 Human and ecological impact assessment. Selection and use of the USEtox model tool. The characterization factors of each pollutant are combined to calculate the impact of the job-shop on the human and ecosystems health.
 - Impact score of base case scenario.
 - Impact score of improved scenarios.

8.3. APPLICATION OF THE METHODOLOGY AND PARTIAL RESULTS

In this point, the methodology mentioned above will be applied carefully and within time the objectives will be obtained for this chapter.

8.3.1. Case study selection and description

Leisure activities at sea are anthropogenic activities that have a potential impact, not only on the marine environment in the use stage (e.g. microplastics) and the end-use stage (e.g. ocean plastic wastes), but also on the manufacturing stage of its life cycle. Surfing is one of the oldest practiced sports on the Planet (UF, 2019). The history of surfing dates back thousands of years, since it is one of the oldest sports on the planet (Hold surf, 2019). In recent times it has been a privileged few sport to become a fashionable sport practiced by thousands of surfers throughout

Spain, even in the marshes and rivers of the interior regions (Total surf, 2019). Currently in Spain the federation of surfers has 27,624 federated (FEsurf, 2019). This indicates that surfing is one of the most practical leisure activities.

The surfboards are not produced in the shipyard industry, though it is within the marine equipment sector. Part of the production processes and the used raw material are the same or very similar. In fact, the most conventional plants that produce boards use FRP (Fibre Reinforced Polymer) materials.

Before choosing the plant to be analysed, different producers in Portugal and Spain have been contacted. For the choice, it has been considered the geographical situation of the plants (factors that influence the accessibility to it) and the availability of the data/information required for the work. Finally, a smaller surfboards factory in Galicia was chosen. The proximity to the author residence and to meet the owner facilitated the communication and data availability.

The plant, situated in Ribeira (Galicia, Spain), is a job-shop with only one employee, or two during the period with more intense work (that generally is taken place in the summer). The employee declared that he works 7 h per day and 6 days per week. In 2016 he produced 140 surfboards. His boards are manufactured following the typical operational steps carried out in most of the plants all over the world. For this, the case study is taken as example between all the similar realities.

8.3.2. Qualitative analysis of the selected industrial sector

The production process requires a series of activities that can be classified in five main stages: external operations, preliminary operations, processing, final operations and auxiliary operations. All stages demand material and energy resources (representing the system inputs), and generate, among the main product, residual flows (representing the system outputs). Material inputs are mainly Polyurethane (PU), polyester resin, catalyst, fibre glass cloth, solvents, water, paints, paperboards and bubble wrap plastic for packaging, whereas energy inputs are fuel and electricity. Conversely the outputs are primarily foam and resin dust, surplus of resin, pieces of fibre glass or others cloth, particle emissions (Figure 8.3 represents “PM” (Particulate matter) and “Non-gaseous wastes”), VOCs emissions and exhaust gases from combustion sources (NO_x, SO_x, CO, CO₂, etc.). In Figure 8.3 the qualitative flowchart of the process is shown.

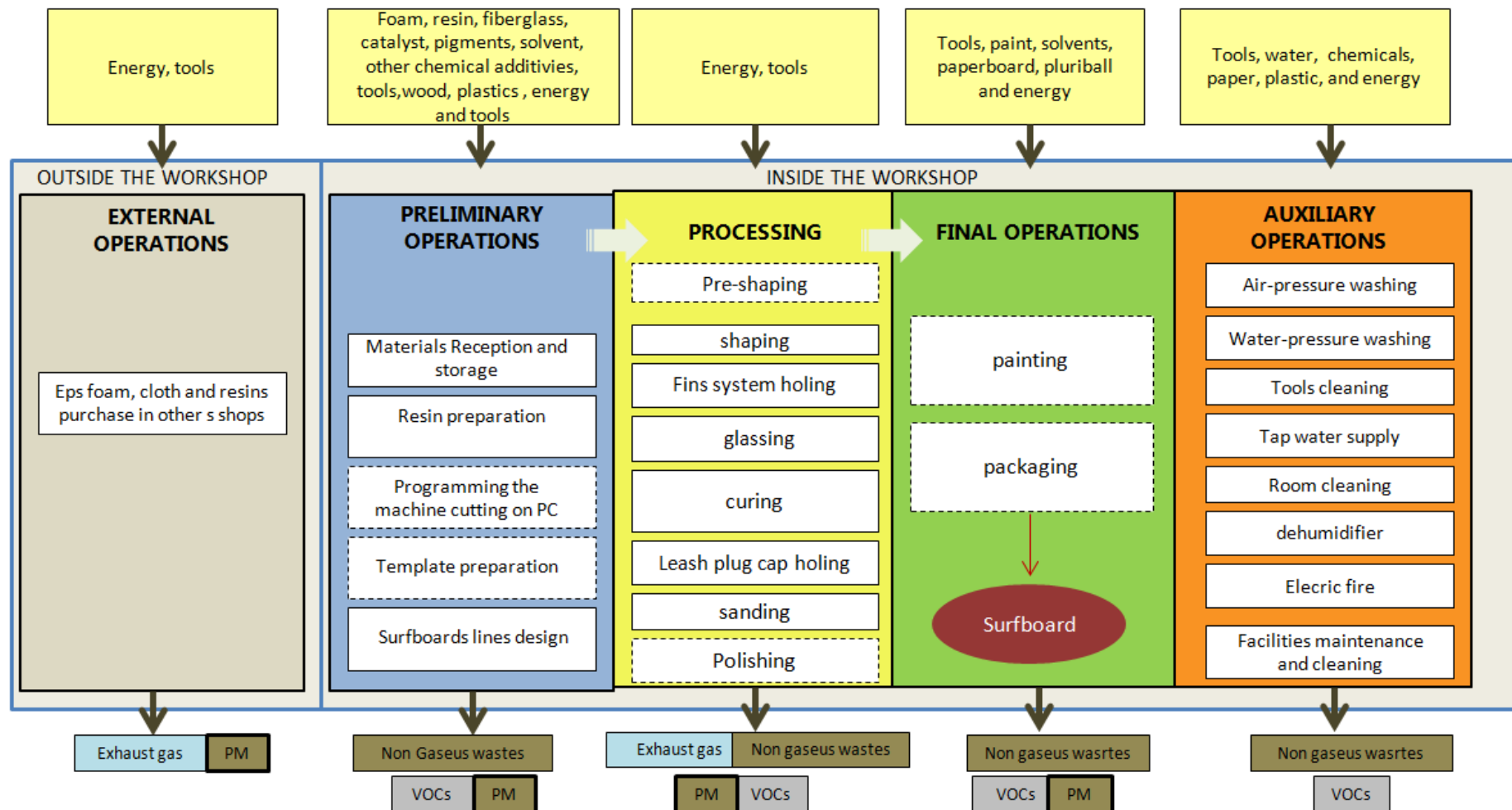


Figure 8.3. Qualitative flowchart of the surfboards production process

8.3.2.1. External operations

There are some operations that are ran outside the workshop. It is the case of the foam, cloth, resin and others material purchase. Some materials are purchased in person by employee who goes to buy them in local or farther shops by the plant. This implies fuel consumption with the emission of compounds such as nitrogen, water, carbon dioxide, but also toxic compounds as carbon monoxide, unburned hydrocarbons, nitrogen oxides, sulphured oxides and particulates.

8.3.2.2. Preliminary operations

This stage is composed of several operations necessary for the following workmanship.

- 1 Material reception and storage. Part of the materials required come from national or international companies which send the goods directly to the plant. This step requires no energy or material; it is a simply unavoidable logistics transition.
- 2 Resin preparation. This operation is needed before starting the glassing and it is carried out in the glassing room. Preparation of the resin is made mixing the polyester or epoxy resin with the catalyst (the exact quantity of each one depends on the specific products, but generally the catalyst is the 2% of the resin). The right environmental conditions to work with resin are a temperature between 20 and 32 °C and a percentage of humidity the lowest possible. In fact, the humidity cannot permit the catalysis and the spoil of the final product. This is because the glassing room has two electric fires and a dehumidifier (it causes the high level of humidity that characterizes the place). The residual flows (VOCs, odours, heat) are mainly those caused by the chemical's usage.
- 3 Programming of the PC software connected with the “cutting machining”. This is not always a necessary operation because the pre-shaping with the cutting machine, it is only sometimes used. In fact, the employee declared that only the 50% of the total amount of the surfboards have been pre-shaped with the cutting machine, whereas the other 50% is completely handmade. The programming includes the PC utilization, with the corresponding use of electricity. The outputs of the operations are indirect and depend on the raw material by his energy company provider.
- 4 Templates preparation. This operation is not always required, because the majority of templates are already prepared. It is necessary to make new ones only when a template does not develop his function anymore, for example, if a template is old, overly used, or when a new specific size not yet shaped before. When this happens, the employee needs a wood foil for cutting to transform it into a new template. Electric and manual saws are used. The worker said that it is difficult to tell how many templates he makes yearly, because this is an irregular market. Wood and sawdust are the waste of the operation.
- 5 Surfboard lines design. Surfboard lines design is the last operation before starting the pre-shaping in the case of 100% handmade surfboards, or the shaping in the case of automatic pre-shaped boards.

8.3.2.3. Processing

The “Processing” stage is the main surfboard manufacturing step. It can be divided into 8 operations which are: the “pre-shaping” (this step is considered only when the cutting machine is used), the “shaping”, the “fins system holing”, the “glassing”, the “curing”, the “leash plug cap holing”, the “sanding” and “polishing” (it is no always carried out). All stages demand material and energy resources and generate residual flows. The entire process is shown in Figure

8.4.

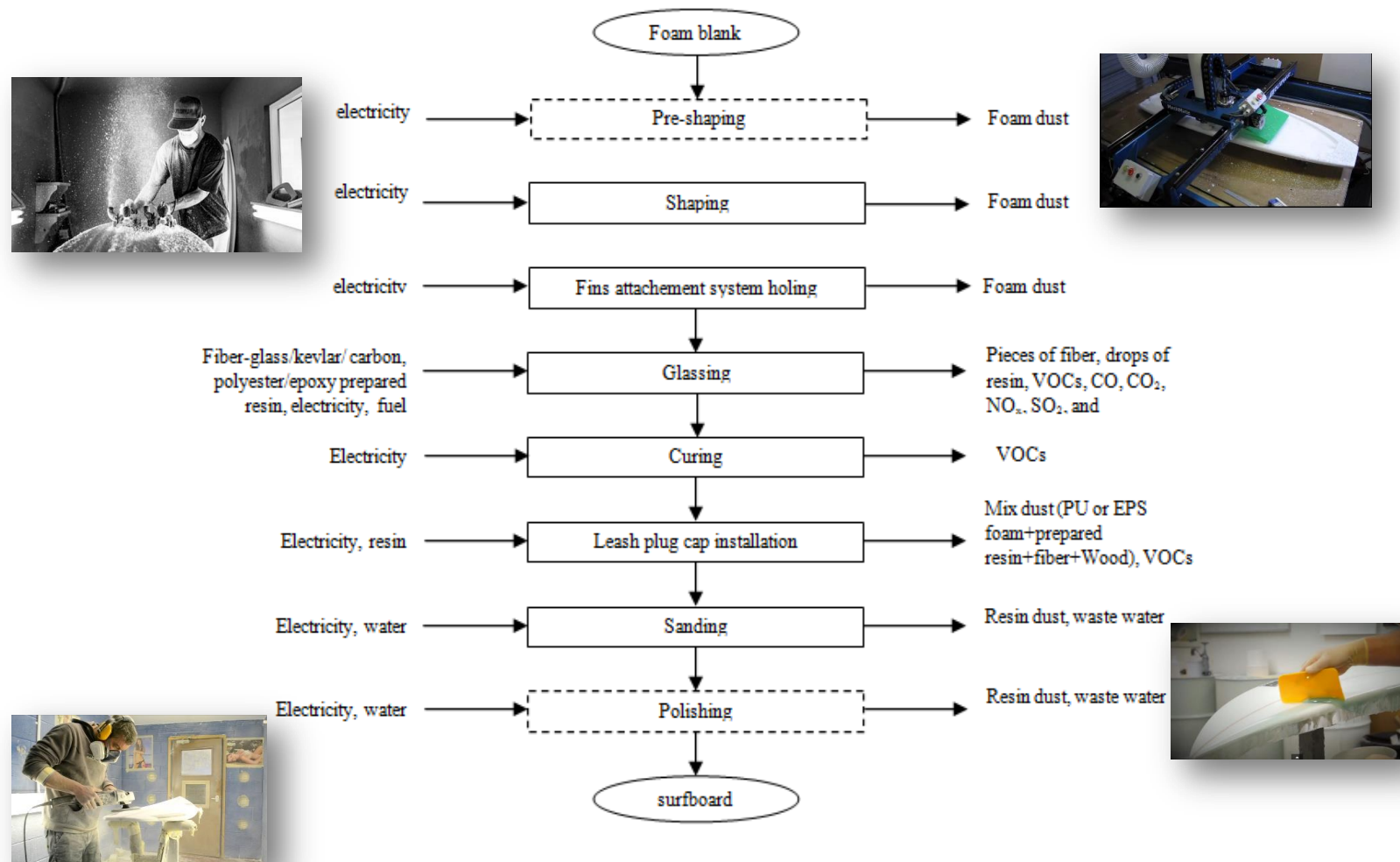


Figure 8.4. Entire processing stage scheme

- 1 Pre-shaping. This operation consists on producing an almost definitive form from starting foam blank. It can be completely handmade or with the help of a cutting machine. The use of the last machine allows of saving up to 50% of the time used for a total of handmade boards. However, only the half of the blank foams receives the pre-shaping with the cutting machine. This operation takes about 30 min per board and then the final shape takes about 1 h, unlike 3 h of shaping for 100% handmade boards. Electricity is always required and the out- put is represented by the dust of the EPS (Expanded polystyrene) or PU (Polyurethane) foams (for this chapter only PU foam is considered).
- 2 Shaping. It is the real job of the shaper to give the right geometry and shape to the board. It consists on the use of a series of tools that permit to achieve the final shape desired. The use of measuring tools, sandpapers, and planer is necessary. The operation takes only about 1 h for the previously drafted foams whereas for the blank foam it takes about 3 h of manual work. As in the pre-shaping step, the input and output are foams, electricity and dust as waste.
- 3 Fins attachment system holing. Before the application of the resin, the holing for the fins attachment system integration is planned. A template is supported on the exact point where it needs to be holed and with an electric router the foam is cut. Then, the fins attachment system is inserted.
- 4 Glassing. This is one of the most delicate operations. The resin used needs a temperature no lower of about 20 but no higher than about 32 °C and a low level of humidity. Otherwise, the catalyst would not have a good behaviour and the solidified resin layer could not maintain the same mechanical characteristics breaking easier. To keep this condition, a dehumidifier and an electric/liquid fuel heater are used. This equipment produces emissions to indoor air (and then to outdoor air) that includes substances such as CO, CO₂, NO_x, SO₂, and formaldehyde among others. Polyester or epoxy resin can be used for glassing, but in the case study the most used is the polyester resin. Furthermore, there are different types of cloth. The most used, fibreglass cloth, which can be of 3 different weights, although sometimes also those of kevlar and nylon or carbon. In this operation, one layer of fibre is unrolled on the bottom surface. This layer of fibre is impregnated with the resin using a spatula. Then, when it dries, he turns the board and unrolls two layers of fibre on the top surface, and again the resin is sprinkled.
- 5 Curing. When resin and fibre are applied together to the foam, it is necessary to wait for the drying. There is a second curing after application the top glassing, and between these steps the leash plug cap is installed. Temperature and humidity must not change respect to the previous step. At this point, the operator cannot make anything upon the current board, so he can work on other operations, or auxiliary operations that suppose no use of the board.
- 6 Leash plugs cap installation. Once the resin is dried, it is time to hole the back part of the board to integrate the plug cap. To do it, a drill is utilized which plough a hole to insert the plug. At this point, the resin is used again to fix the plug cap to the board. By the moment the drill cuts through the FRP layer, it goes in deeper and the dusts that comes out are a mix between resin, fibre, and foam. Furthermore, due to the plug cap is always integrated along the axle of the board, which coincides with the stringer, a big part of the dust is composed by the wood.
- 7 Sanding. It is the operation in which the electric sander is used to make the board surface smooth and homogenous. During this operation different disks of abrasive paper, fine and coarse, are used to apply on the sander. To wipe out the dust from the board, a flow of compressed water can be used. In this operation the wastes are the resin dust and the waste water (with suspended particulate).

- 8 Polishing. This operation is not always carried out. It is needed when you want the board surface shines. The effective step to reach it, depends on the level of gloss required. In general, it is supposed that greater resin layer is applied at the moment of glassing and an extra sanding with a finer abrasive paper. Outputs are the same as for the sanding step.

8.3.2.4. Final operations

Final operations include those operations that are carried out additionally as complementary, but that are not functional to the production of the surfboards. These are the painting and the packaging.

- 1 Painting. When it is required by the client, the employee utilizes acrylic paints and lacquer to fix it. The waste of the painting operation is aerosol of paint, VOCs, dirty paper and empty paint cans. The painting operation is carried out after sanding on the resin layer. If the graphics extends on the whole surface, it can be carried out before glassing directly on the foam. This does not mean that it should be used as a complementary operation.
- 2 Packaging. Employee declared that some of the manufactured surfboards are picked up by the client, but others are packaged and shipped. For this operation, carton boxes and bubble wrap are consumed, and a small quantity of tape.

8.3.2.5. Auxiliary operations

Additional operations are necessary to obtain a correct outcome of the whole process, i.e., in order to ensure the quality of the product. These auxiliary operations consist mainly on water and electric supply. Water is used for cleaning, especially after glassing (also for ordinary use of the bathroom) and the electric supply is used electric equipment and lighting. Cleaning and maintenance of the work equipment, tools and facilities, are operations which are included in this step.

- 1 Air pressure washing. During shaping, to wipe out the dust from the foam form is important, with an electrical air compressor. The dust will spread all around the shaping room.
- 2 Water pressure washing. After sanding, a flow of compressed water is used to clean the resin dust board. The operation is performed with the use of a water compressor connected to tap water supply. The dust and the water will be on the floor although the water will evaporate.
- 3 Tool cleaning. The main important tools to be cleaned are those that were in contact with the resin. In order to wash them, they are soaked in a recipient with acetone, the enough time to dissolve the resin. Then the acetone will evaporate. It is estimated that 130 L of acetone per year is consumed.
- 4 Tap water supply. This stage includes all operations which use tap water, like water pressure washing, but also hand washing, use of toilet and others.
- 5 Room cleaning. Due to the big quantity of dust and other particles and drop of resin and paint, the whole plant needs to be cleaned periodically. The employee said that every 10–15 days he throws away the plastic and the paper that remains on the pavement in the glassing room. But all other spaces need to be cleaned up for the big amount of dust that stays everywhere.
- 6 Dehumidifier. It is required in the glassing room to maintain a low humidity level. Electricity supply is necessary.
- 7 Electric fire. To keep a specific temperature in the glassing room is also required, for this an electric/liquid fuel heater is utilized.

8.3.3. Quantitative analysis of the selected industrial sector

In this point the material and energy data directly acquired at the workshop is shown. They will be mentioned in order of usage during the manufacture process. Not all data has been easily acquired. Part of them, were necessary for the material and energy flows networks modelling that were calculated later indirectly. Although a small part of the materials listed are not analysed because of the lack of data, and the associated environmental aspects have not identified as potential in the qualitative analysis.

The reference year for this quantitative analysis is 2016, both data acquisition and modelling.

8.3.3.1. Material data

One of the most important materials used is the polyurethane blank foam, which represents the core of a surfboard. The employee imports from a seller of Cádiz (South of Spain) the shapes, which are produced by a South African company. Depending on the size of the board to be produced, the employee starts to work with a blank of an adequate size. Because of this, the employee imports different sizes, in order to avoid modelling big blank foam when he intended to manufacture a small size surfboard.

8.3.3.1.1. *Shaping*

The shape sizes are expressed as foot and inch, representing the length, the width and thickness of the shapes. The most common shape size is shown in the Table 8.1, including the weight and the wood stringer, because the shapes came with it already installed. In this study, the shape more used is considered as reference due to the following points:

- 1 No reliable information about the number of each different board sizes manufactured in 2016 was provided.
- 2 The owner declared that size was surely the most worked. Final results of this study are influenced by this simplification decision.

During shaping, the blank loses an important quantity of foam that is now available as dust and scrapes. When shaping ends, the foam weighs 1.3 kg. To simplify the calculation in this study, the weight of the scraps appears included into the weight of the dust, i.e. all the material discarded during the shaping is considered as dust.

8.3.3.1.2. *Glassing*

In the glassing room fibre glass of different weight are applied, as well as various resins and catalyst, producing scraps as waste. Table 8.1 shows the quantity of materials utilized and waste generated.

8.3.3.1.3. *Sanding*

In order to ease the sanding operation, a quantity of paraffin is mixed with the resin to make the gel coat. To perform the process, temperature needs to be maintained between 20 and 32 °C, for this, an electric/liquid fuel heater is turned on, which it is estimated to burn 6 L of kerosene per year. Lamination process, lasting 45 min, requires a heater and a dehumidifier turned on. Data of this stage is shown in Table 8.1.

Table 8.1. Input materials in the case study

SHAPING	Size (Foot and Inch)	Size (Cm)	Weight (kg)	Weight after shaping (Kg)	
	6'4''	193.04	2.50	1.30	
GLASSING	FIBRE GLASS				
	Rolls	Weight (g/m ²)	Length (m)	Total length (m)	Total Weight (kg)
	6.00	125.00	110.00	660.00	82.50
	1.00	190.00	110.00	110.00	20.90
	SCRAPS				
	Weight per board (g)				
	175.00				
	POLYESTER RESIN				
	Barrels		Weight per barrel (kg)		
	2 to 3		230.00 (17.00 kg empty barrel)		
	EPOXI RESIN				
	Weight (kg)				
	20.00				
	CATALYST				
	Percentage		Weight (kg)		
	2.00%		≈13.80		
	ACETONE (Kg)				
130.00 Kg					
SANDING	PARAFINE		KEROSENE		
	Weight (kg× year)		Volume (l × year)		
	15.00		6.00		
	WATER				
	Weight (kg)				
140.00					
PAINTING	PAINT				
	Can		Weight per can (g)		
	5		270.00 (180.00 g empty can)		
	LACQUER				
	Can		Weight per can (g)		
5		270.00 (180.00 g empty can)			
PACKAGING	CARTON BOXES		BUBBLE WRAP		
	Units	Weight (kg×box)	Length (m ² ×board)		Weight (kg)
	50	3.16	5.00		39.00

8.3.3.1.4. Packaging

For the packaging the use of carton and bubble wrap is planned. According to what the owner said, the 40% of the surfboards leave the workshop to be sent. The material data of this stage is shown in the Table 8.1.

Among these principal materials, an important amount of auxiliary materials is consumed. Table 8.1 shows different auxiliary materials (acetone and water). The data relative to the amount of generated waste and emissions were not directly available. These data were estimated and they are shown in model and scenario building.

8.3.3.2. Energy data

All the information concerning electricity and energy consumption during 1 year of work was completely unknown. Because of this, in the job-shop the brand and the model of the electric tools used have been checked. Later, information about the electricity and energy consumption of those tools that do not show this data in their data sheet are searched. Table 8.2 shows the characteristics of the electric tools used in this chapter to know the relative electrical and energy

consumption. These data are used to estimate the electric consumption considering the time of usage for each electric tool.

Table 8.2. Technical data of the tools (The cursive information means the data is calculated, whereas the others are data from the data sheet)

Tool	Electricity Intensity (Ampere)	Voltage (Volt)	Power (Watt)
Personal computer			70.0 (pc) + 40.0 (monitor) = 110.0
Cutting machine			830.0
Electric planer	7.5	220.0	1650.0
Electric router	340.0	3.1	710.0
Air compressor			(2 hp)= 1470.0
Dehumidifier			240.0
Electric heater			150.0
Electric polisher	6.4	200.0-240.0	
Water compressor	6.0	200.0-240.0	1440.0
Vacuum cleaner		230.0	1100.0

8.3.4. Model and scenario building

The case study was modelled for 1 year (2016) considered the most adequate for the plant activity (analysing all the stages of the plant, the most and the less work repeated every year in the same times). In fact, this activity is very variable during the year and it depends firstly on the client demand, although other factors can change the production intensity. For this reason, and according to the objective of this chapter, the developed model is a steady state model. MEFA is an adequate tool to identify the improvable flows. As demonstrated in another work (Torres Rodríguez et al., 2011) for quantitative study, the flows direct data are put into the model, whereas the unknown data are calculated and/or estimated. When these last data are put into the software, the model is ran, the scenario with his calculated flows is obtained represented by Sankey diagrams, and the MEFA is made.

8.3.4.1. Software selection

To build the model of the base case scenario, three different types of software are considered and evaluated: ASPEN HYSYS (a process simulator), Umberto (specific and commercial MEFA software) and STAN (non-commercial and specific MEFA software). ASPEN HYSYS and Umberto, even if they are stated software, they are more suitable to develop the quantitative analysis for other types of systems, as stated Cristobal Andrade et al. (2014) for the Aspen HYSYS, and Taboada Gómez et al. (2016), Torres Rodríguez et al. (2011) and Bello Bugallo et al. (2012) for Umberto. On the other hand, STAN is a free software that permits to perform MEFA for simpler systems, thanks to a simple and clear graphical interface, and easy to use.

8.3.4.2. System modelling

In this point all the calculations and/or estimations and the implementation of STAN for each flow are presented.

To build the model in STAN, flows and stocks network is implemented. STAN uses predefined components named: “processes”, which are the stocks, “flows”, “system boundary” and auxiliary text field.

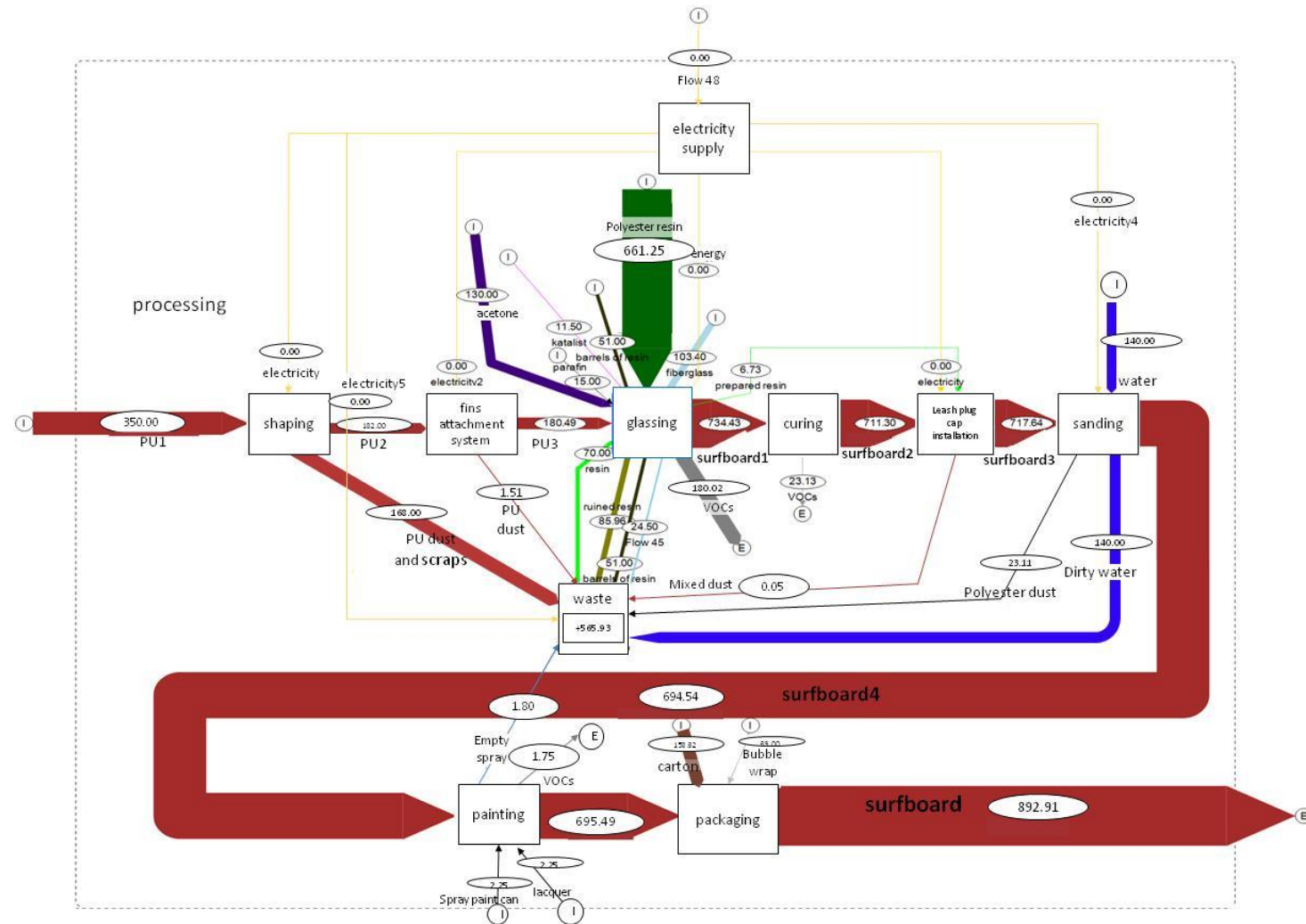


Figure 8.5. Material Sankey diagram obtained for the Glassing process. Expressed in kg/year

The processes are represented by polygonal boxes, the flows by arrows and the system boundary by closed dotted lines. In Figure 8.5 (the process already resolved in STAN) the quantitative network of the whole production process can be seen: in yellow the electricity (energy) flow, and the rest of colours for material flows.

In this model the external operations to the job-shop have not been examined. It considers all the workshop internal operations, even if those are not directly connected with the manufacturing work. These last (e.g., “room cleaning”) have been considered, although they are carried out occasionally because of their inputs and outputs (see Figure 8.3). The only limit is the impossibility to visualize both material and energy flows at the same time. For this reason, the system model with the results will be shown in two separated figures.

Data used to the material and energy flows diagrams are those relative to the year 2016, thus the quantities of mass and energy are expressed on annual base. The material unit is the kg whereas for the energy is the kWh.

8.3.4.2.1. *Material flow analysis*

The explanation of material flow analysis is presented following the considered steps in the whole process:

- 1 Shaping. In the shaping operation the material input is the polyurethane represented by the blank foams whereas the outputs are represented by the shaped foams and the residual dust. According to the surfboard size, to calculate the amount of PU flow, the surfboard size most produced is considered: the 6 in. 4 ft size (Table 8.1).

Table 8.1 shows the initial and final weigh for each board. To sum up, the process produces a loss of 48%. This percentage is entered as Transfer Coefficient (TC) in the information schedule of the operation to compute the total amount of the output flow, 182 kg of shaped polyurethane foams and 168 kg of polyurethane dust respectively.

- 2 Fins Attachment System. In order to calculate the dust generation during this operation, the filled volume by an average fin is considered. This is because of that some boards are equipped with 3 fins, but others with 4 or 5. For this reason, the average volume of polyurethane foams that is extracted from the shaped foam is $0.3 \times 10^{-3} \text{ m}^3$. Knowing the polyurethane density (36 kg/m^3) and the number of produced boards per year (140), the estimated dust quantity is 1.51 kg.
- 3 Glassing. This is a “sub-system” because it includes two operations, the resin preparation and the real glassing operation. For resin preparation, according with the producer information, 661.25 kg of resin are yearly used. For other hand, 13% of it gets ruined and it is dumped in the trash together with the iron barrels (17 kg each one). Furthermore 2% of catalyst is added to the resin. The 99% of this prepared resin represents the output that going in the glassing operation, whereas the other 1% represents the input of the “leash plug cap installation” operation.

In the real glassing operation, the polyurethane foam and the prepared resin come from previous steps. Furthermore, the paraffin (15 kg) and the fibre glass (103.40 kg total) that Table 8.1 shows are used. The main output is fresh glassed board, a total weight of 753.79 kg. Although there are undesirable outputs: the lost resin on the floor, 70 kg (0.5 kg per board), the fibre glass scraps, about 24.5 kg (part of them will be reutilized for reparation operations and another part is dumped) and the VOCs.

For calculation of the VOCs preceded from the styrene in the resin, the South Coast A + QMD guideline document (AQMD, 2016) is used, which suggests to estimate the VOCs emissions with the Eq. (8.1).

$$Emission (Kg) = Throughput \times Emission Factor (EF) \quad [Eq. 8.1]$$

- 4 VOCs from gel coat application. For the gel coat, the EF (Emission Factor) is calculated with Eq. (8.2), where S is the Styrene quantity considering that resin contents 36% of styrene, concentration (Hergardt, 2018), the paraffin has a styrene content of 95% and is mixed at 5% weight to the resin to form the gel coat.

$$EF = (0.4506 \times S) - 0.0505 \quad [Eq. 8.2]$$

The emission is calculate applying the Eq. (8.1) and knowing “Throughput” (15 kg of paraffin represents the 5% weight of the gel coat, the rest 95% weight is resin, and they are 255 kg). This value is shown in Table 8.3.

Table 8.3. VOCs			
VOCs			
GLASSING			
Gel coat application (Kg)	Resin application (Kg)	Acetone (Kg)	TOTAL (Kg)
33.750	16.270	130.000	180.020
CURING			
Gel coat application (Kg)	Resin application (Kg)	TOTAL (Kg)	
15.000	8.125	23.125	
LEASH PLUGS CAP INSTALLATION (Total Kg)			
0.0336			
PAINTING (Total Kg)			
1.750			

- 5 VOCs from resin application (the emissions of the resin lost in the floor is also included) EF for the resin application is calculate with Eq. (8.3), where S is the Styrene quantity ($S = 0.36$). The same way that in gel coat application, “Emission” is calculated with Eq. (8.1) and the value is shown in Table 8.3.

$$EF = (0.286 \times S) - 0.0529 \quad [Eq. 8.3]$$

Another input that appears in glassing process is the Acetone. This solvent is used to remove the residual resin from the utensils, which confers it utility linked to tools cleaning. Producer declared to consume 130 kg of acetone per year, but to never dump it as waste liquid because all the acetone he uses ends vaporized. So, the total VOCs from the use of acetone are 130 kg as shown in Table 8.3. It is good to specify, especially at the time to estimate the human and ecological toxicity, that the organic compounds of this emission are different from resin and gel coat VOCs: acetone the first and styrene the second. Anyway, the total VOCs emission amount in the “Glassing” is shown in the Table 8.3.

The electric/liquid fuel heater burns paraffin emitting substances to the air, making even worst its quality. For to estimate these emissions, the work of Hanoune and Carteret (2015) is referred, in which the emission of 7 fuel (kerosene) heaters are monitoring for 1 week. The results are shown in the Table 8.4 (column 2) and compared with the suggested limits values of emission for 1 h (the operating of the heater is of 45 min) of the WHO guidelines for indoor air quality (WHO, 2010; ASHRAE, 2010) and those required with the European Directive 2008/ 50/EC (EU, 2008).

Table 8.4. Average emissions from the fuel heater and relative limits (The concentration that not exceed the limit is green, in red those that exceed the limit) (Hanoune et al., 2015; WHO, 2010; ASHRAE, 2010; EU, 2008)

Substance	Average concentration (Hanoune et al., 2015)	Limit value
CO	0.200 - 12.000 ppm (13.940 mg/m ³)	35.000 mg/m ³ (WHO, 2010)
CO ₂	Peaks till 3500.000 ppm	5000.000 ppm (ASHRAE, 2010)
NO ₂	0.200 ppm	0.200 mg/m ³ (0.110 ppm) (EU, 2008)
SO ₂	0.001 - 0.0137 ppm	0.350 mg/m ³ (0.130 ppm) (EU, 2008)
Formaldehyde	0.007 - 0.012 ppm	0.100 mg/m ³ (0.080 ppm) (WHO, 2010)

As clearly showed in Table 8.4, in the study (Hanoune and Carteret, 2015) the concentration of NO₂ exceeds the limit value, whereas the concentration of SO₂ and formaldehyde are practically negligible. The information about the concentrations of CO, CO₂, NO₂, SO₂ and formaldehyde, do not have data available of total emissions per year. Therefore, these components will be not considered when calculating the IA of human health and ecosystems.

- 6 Curing. The estimation of VOCs emissions during curing time, was possible adopting the Eq. (8.1) in the South Coast AQMD guideline document (AQMD, 2016), and considering the “covered-cure without roll-out”. As made previously, it is necessary to separate the emission from curing of gel coat and the emission from the curing of the resin application. In this case, Eq. (8.4) is used to calculate EF and the emission values are shown in Table 8.3.

$$EF = 0.5 \times EF \text{ relative of the direct application} \quad [\text{Eq. 8.4}]$$

EF relative of the direct application is the EF calculated before in gel coat application and resin application for both emissions.

- 7 Leash plugs cap installation. About 0.05 kg of dust (a mix of PU, wood, fibre and resin) are generated during the operation. This waste has little significance respect to other flows. Because of this, his accurate characterization resulted unnecessary. VOCs emissions from the resin application are calculated with the equations 8.1 and 8.3 and his value is shown in Table 8.3. The resin used is the 1% (6.73 kg) of all the prepared resin during the “resin preparation” operation and represents the input flow as well as the cured board flow.
- 8 Sanding. At the end of sanding operation, water to wash boards is used to remove away the residual resin dust from the surface, and it was declared 1 L per board i.e. total weight 140 kg. Weighing the board before and after the sanding operation, the difference was 0.17 kg, which means any surfboard loses the 0.0322% of the original weight. Then, the total amount of dust is 23.80 kg.
- 9 Painting. To model this operation with congruent value of paint input and lacquer was not simple cause the scarce information from the producer. After different considerations, pigments paints are not taking account for two reasons: first, the producer affirmed that the desired colour uses a very low quantity of pigment. Second, the pigments are not dispersed and they will not represent an emission because all necessary pigment finishes in the resin (painting with pigment and glassing is made in parallel). The only paints considered are the spray paint cans, which also generate other outputs.

Although the producer was not able to say how many spray cans per year are used, in the moment of the interview, the producer said to have 20 spray cans and many of them by different years, for this a random number of 5 cans are considered. Table 8.1 shows the quantity of paint, lacquer and cans used at year. Estimating, the total weight paint is 2.25 kg and the same quantity of lacquer. The producer uses the lacquer spray with the same

physical characteristics of the spray paint cans to recover the same painted surface. At time, on the other hand the outputs are represented by the empty cans and VOCs. For the first output a total of 1.8 kg is calculated; for the second one, the emissions are shown in Table 8.3. These emissions are estimated of 100 g/m² of painted surface (EU, 2017). It is estimated that one spray can of 400 mL, paints 1.75 m².

- 10 Packaging. Half of the surfboards made will be sent away the workshop. Table 8.1 shows the quantity of paper box used and his weight. Regarding the calculation of the density of the bubble wrap, different data sheets have been consulted, so the considered average is 60 g/m² (Ozerden, 2017). Density permits to estimate the weight of bubble wrap shown in Table 8.1.
- 11 Waste. This is not a real operation. Table 8.5 shows and represents the accumulation of the solid waste/by products from each operation.

Table 8.5. Accumulation of the solid waste / by products from each operation

MATERIAL	QUANTITY (Kg)
Dust	169.51
Polyester resin	70.00
Ruined polyester resin	85.96
Iron barrels	51.00
Mixed dust	0.05
Polyester resin dust	23.80
Dirty Water	140.00
Empty spray cans	1.80
TOTAL	542.12

Total solid waste is 542.12 kg, although unknown percentage of fibre glass should add. The producer affirms that 24.50 kg of fibreglass is reutilized for reparations operation. So, admitting this model of the surfboard manufacture process, a maximum variation of the stock of 4.51% is estimated.

On the other hand, the “waste” stock can also be interpreted as a process operation, because of occasionally the workshop is cleaned of the dust with a vacuum cleaner which needs electricity supply, for this appears a pure energy input.

8.3.4.2.2. *Energy flow analysis*

In this section, electricity consumption of the tools used during the manufacturing of the boards is calculated and estimated. For the glassing operation, electricity and thermal energy is required. Anyway, the total energy needed by the whole process is expressed in kWh/year, being 2016 the year of reference. The estimations are based in the observations in situ, interviews with the owner, as well as the few data available. As the focus of this chapter is on the methodology, besides the uncertainty of the data and assumptions to calculate the base case scenario and the improved scenario, it is not considered relevant for the whole results and conclusions of the work.

Due to the lack of energy consumption information, the efficiency of the electrical equipment is considered 100% to compare scenarios by improving the base case.

- 1 Shaping. It is considered that 50% (70) of the boards are entirely handmade. The other 50% received a pre-shaping with the cutting machine and the final shaping operation is also handmade. Table 8.6 shows the time of use and electric consumption of each machine
- 2 Fins installation. For this process, the electric router is used during 15 min per board for the cutting of the geometry, where the fins will be installed. Its consumption is shown in Table 8.6.

- 3 Glassing. During the glassing the dehumidifier and an electric fire are used to ensure the correct conditions of humidity and temperature. Their consumptions are shown in Table 8.6.

For to estimate Energy consumption from the fuel combustion, to know the Paraffin Calorific Value is necessary (43.45 MJ/kg (it is an average of the maximum and minimum values (Engineering ToolBox, 2017) = 12.07 KWh) and Paraffin Density (=0.87 kg/L).

- 4 Leash plugs cap installation. 30 s are estimated for the cutting of this geometry on the board, using the same electric tool that in fins installation. The electricity consumption is shown in Table 8.6.
- 5 Sanding. The use of air and water compressors during 30 s each board is estimated, which means 70 min (1.16 h) per year. The electricity consumption is shown in Table 8.6.
- 6 Waste. During cleaning operation, the use of the vacuum cleaner is contemplated. According with information from the plant, this electric tool is used during 5 h per month. The electricity consumption is shown in Table 8.6.

8.3.4.3. Model running and results

For running the model, an interesting option that the software provides is used: the TC. Entering the TC in a process, the outputs turn to be on function of the inputs, or vice versa. Because of this, sometimes distribution of the amounts of material to the outputs (or to the inputs) is calculated with this option.

Once all input data of the model are implemented and output data are calculated by simulation in STAN, the scheme is converted on a Sankey diagram. In this diagram the thickness of the arrows of flows are in proportion to the amount of the material and/ or energy.

The results for the material flows are shown in Figure 8.5 and Figure 8.6. These, represent the entire diagram of the production model and Glassing process sub-system respectively. Figure 8.7, shows the results of the energy analysis. It is important highlight that in this chapter 100% energy performance is supposed. In fact, the analysis is restricted to the electricity and thermal energy supply, so only the input flows are shown, whereas the outgoing energy flows are excluded. For this reason, the BAT analysis only considers the energy consumption (input).

Table 8.6. Energy data

SHAPING								
		Boards with cutting machine pre-shaping						
Planer use		Cutting machine		PC programme		Planer		
Time	Consumption	Time	Consumption	Time	Consumption	Time	Consumption	TOTAL consumption
21.00 h x year (3.00 h X board)	346.50 kW/year (1.65 kW x board)	2.00 h	0.83 kWh	0.50 h	0.11 kWh	0.50 h	1.65 Kw X year	466.20 kWh/year
FINS INSTALATION								
Electric router								
Time				Consumption				
3.50 h x year 15.00 min				2,485.00 kWh/year (710.00W)				
GLASSING								
Dehumidifier		lighting of the flame				Fuel combustion		
Time	Consumption	Time		Consumption		Volume (l x year)		Consumption
105.00 h x year (45.00 min x board)	25.20 kWh/year	70.00 h x year (45.00 min x board)		63.00 kWh/year		6.00		63.00 kWh/year
LEASH PLUGS CAP INSTALLATION								
Cutting machine								
Time				Consumption				
1.16h (30.00 sec x board)				0.83 kWh/year (710.00 W)				
SANDING								
Air compressors				water compressors				
Time		Consumption		Time			Consumption	
1.16h (30.00 sec x board)		1.71 kWh/year (1.47 kW)		1.16h (30.00 sec x board)			1.67 kWh/year (1.44 kW)	
WASTE								
Vacuum cleaner								
Time				Consumption				
60.00 h per year				66.00 kWh/year (1100.00 W)				

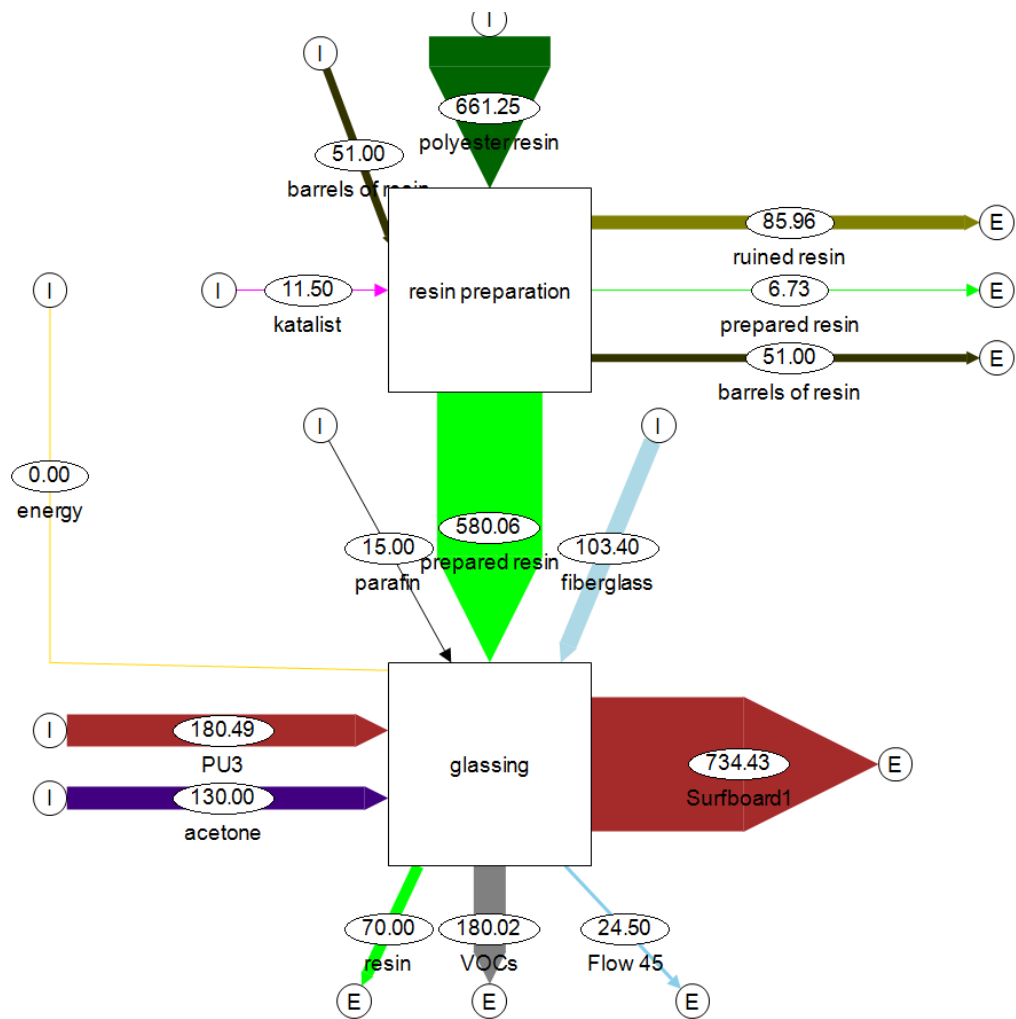
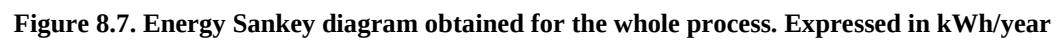


Figure 8.6. Material Sankey diagram obtained for the Glassing process. Expressed in kg/year



8.3.5. Selection of improvable flows

According to the results of MEFA, six stages have been proved to be improvable, because of their high resources consumption or emissions. In the “shaping” operation almost the 50% of PU is unwrap from the foam blank that will represent the only one output of the stage (PU dust and scraps). In the glassing, improvable flows are identified in both the “resin preparation” and the “glassing” operations. In the first one, the wastage of resin (ruined resin output) could be eliminated or reduced and therefore the relative number of barrels too. The second one, in the glassing operation the use of acetone and its emission could be minimized with an improvement in management of the product. Other more ecological heating and dehumidifying systems could reduce electricity need. In the “sanding” operation, the use of water represents an improbable flow and so its relative output. As consequence of this, it could reduce the electricity use (represented by the water compressor). To carry out the “painting” operation, the spray cans could be substituted with others less toxic and with less VOC emissions (water-based spray cans) in order to improve the VOCs output of this process. Table 8.7 resumes the IF according with the nature of the flow (input or output –for the materials- or energy flow).

Keeping in mind the previous IF, BAT analysis will show all candidates to be BAT to improve the identified flows, but also other aspects of the production process.

Table 8.7. Potential IF identified after evaluating the results of MEFA (the flows names appear as in Figure 5 and 7)

Operation	Improvable Flow		
	Input	Output	Energy
Shaping	PU	PU dust and scraps	Electricity
Resin preparation		Ruined resin (barrels)	
Glassing	Acetone	VOCs	Energy (thermal and electricity)
Sanding	Water		
Painting	Spray paint cans		
Waste			Electricity

8.3.6. Best Available Techniques (BAT) Analysis

The BAT analysis follows the same methodology that other works (Barros et al., 2007b). The Best Available Techniques, referenced in the BREFs documents are developed under the IPPC Directive and the IED (Industrial Emissions Directive) (EU, 2010a). BATs are useful technical indications on the “most effective ‘techniques’, which includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned” (EU, 2010a). BATs are ‘available’ too, namely, “those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions. This is taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator” (EU, 2010a). Effectively the European Commission proposes, in the action plan for the CE, to improve a more efficiently use of resources and to produce less waste is also to adopt a best waste management and resource efficiency practices, following the BREFs indications (EC, 2015b, 2015c).

The inventory of the possible Best Available Technique (candidates) is done after consulting different documents about FRP industries, resins or emissions of styrene among others (EPA, 1991; Kong et al., 1996; EC, 2016a; EC, 2007; Darryl Davis, 1987; EPA, 1993; Torres Rodríguez et al., 2006; Andros, 2016).

Table.8.8 shows the elaborated inventory of candidates to be BAT for the surfboards manufacturing. The BAT candidates are organized by stage of the process, and environmental aspect. The Table.8.8 shows also the level of implementation of the candidate BAT in the case study, including the “already implemented”, “no applicable” (that means that the technique doesn't is BAT for this plant due economical or technical reasons), or including a green tick. BAT candidates with a green tick are the selected to build the improved scenario from a sustainable point of view. The considered criteria to include a technique in the improved scenario are mainly those that act upon the Improvable Flows identified in the previous step. In general, these techniques prevent/reduce the electric consumption, material consumption, and VOC emissions. The preferred techniques are those that can be quantified to give an estimation of the improvement of the scenario. Finally, fifteen BAT candidates are selected to be implemented. Table 8.9 shows the selected BATs with their relative benefit values. The benefits are not quantifiable for all the selected techniques. Combining the above techniques, very important improvements on waste management could be achieved, both on the emission of volatile compounds and particulate matter.

Table.8.8. Inventory of the candidate BATs for the case study

Process stage	BAT candidate	Environmental achievements	Selected BAT
General	Limit the number of potential emission sources	VOC emissions reduction	Not applicable
	Maximize production runs	VOC emissions reduction	Not applicable
	Re-usable containers	Reduced waste	
	Ensure the isolation of the different work spaces the more efficient possible, to avoid high air exchange.	contamination reduction of VOCs and PM free work space	✓
	Ensure robust plant/equipment commissioning and handover procedures in line with the design requirements	Reduction VOC emissions	
	Computerized inventory control	Material waste reduction	✓
	Solid waste segregation	Environmental benefits	✓
Glassing	Restrict solvent issue	Reduction VOCs emissions	
	Store and reuse cleaning solvents	Reduction of VOCs emissions and hazardous waste	✓
	Use less toxic and less volatile solvents	Reduction of VOCs emissions and hazardous waste	
	Reduce solvent rinse usage	Reduction VOCs of emissions and hazardous waste	
	Improving recyclability of solvent waste	Reduction VOCs of emissions and hazardous waste	

Process stage	BAT candidate	Environmental achievements	Selected BAT
Glassing	Replace solvents with emulsifiers	Reduction VOCs of emissions and hazardous waste	
	Modify resin pan geometry	Reduction of solved resin and VOCs.	Not applicable
	Reduce transfer pipe size	Reduction of solved resin and VOCs.	Not applicable
	Improve material application procedures	Material waste and VOCs reduction	
	Spray orientation	Reduction of solved resin and VOCs.	
	Non-spray resin application methods	Reduction of solved resin and VOCs.	Already implemented
	Tighter inventory control	Material waste reduction	
	Floor coverings	Floor clean-up product reduction	Already implemented
	Self-cleaning equipment	Reduction clean-up rags	
	Cover containers and vats	Material usage and VOCs reduction	✓
	Ensure good maintenance and timely replacement of equipment	VOC emissions reduction	
	As far as it is reasonable, prevent diffuse VOC emissions, collect them at source, and treat them	VOC emissions reduction	
	Filtration	Less waste water production and less use of fresh solvents	
	Select high-integrity equipment	VOC emissions reduction	
	Facilitate maintenance activities by ensuring access to potentially leaky equipment	VOC emissions reduction	
	Use a risk-based leak detection and repair (LDAR) programme	VOC emissions reduction	Not applicable
	Calculation of emissions based on emissions factors, periodically validated (e.g. once every two years) by measurements	VOC emissions reduction	
	Distillation	The amount of hazardous waste is reduced and the solvent can be re-used	
Resin preparation	Conserve the resin between 18 to 25 grades Celsius.	Better resin conservation	✓
	Use smaller barrels of resin	it is avoided to leave the unused resin for a lot of time, which allows its undesirable polymerization	✓

Process stage	BAT candidate	Environmental achievements	Selected BAT
Resin preparation	Add a nitro diluent	It avoids the undesirable polymerization	✓
	Changing resin formulation	Reduction VOCs emissions	
Glassing/painting	Recovery of used solvents from wipes	The recovered solvents can be used again for cleaning, or if too dirty, distilled and re-use.	
Glassing/curing/ Painting	Negative pressure in drying	Reduction of fugitive VOC emissions. Negative pressure causes air to flow into the oven and favours the capture of VOC vapours from the wet coating entering the oven	
	Air extraction from coating processes	Reduction of fugitive VOCs emissions	✓
	Air extraction from drying(curing) processes	Reduction of fugitive VOCs emissions.	✓
	Thermal oxidation	Reduced VOCs emissions to air	
	Increase of the internal or external solvent concentration	Reduction of solvent emissions and lower energy consumption	
	Increasing the external air concentration using a plenum	Reduction of solvent emissions and lower energy consumption	
	Membrane filtration	The VOCs in the VOC rich permeate can be recovered	
	Absorption to water	Removal of gaseous pollutants, such as NO _x , hydrogen halides, SO ₂ , ammonia, hydrogen sulphide or VOCs	
	Catalytic oxidation	Reduced VOCs emissions to air	
	UV oxidation	Reduced VOCs emissions to air	✓
Glassing/waste	On-site solvent recovery	Reduction VOCs of emissions and hazardous waste	
	Off-site solvent recycling	Reduction VOCs of emissions and hazardous waste	
Shaping	Direct or indirect cooling	VOCs can be recovered and possibly re-used	
	Refrigeration	VOCs can be recovered and possibly re-used	
	Cryogenic treatment	Reduced VOCs emissions to air	
	Condensation above freezing point	Solvent recovery	
	Adsorption using activated carbon or zeolites	Reduced VOCs emissions to air	

Process stage	BAT candidate	Environmental achievements	Selected BAT
Shaping/ glassing/ curing	Encapsulation/enclosure	Reduces fugitive emissions and noise. Reduces volume of air to be extracted (and therefore energy used) and reduces size of, and energy used in, any waste gas treatment	
	Local exhaust ventilation	Air quality	Already implemented
Shaping/glassing/ curing/painting	Bypassing peak emission flows (peak shaving)	energy consumption	
	Utilising over-capacity - smoothing variations	Reduction of solvent emissions and lower energy consumption	
	System maintenance	Reduction in overall emission loads	
	Maintaining solvent concentration to treatment by variable frequency drives	Reduction of solvent emissions and lower energy consumption	
	Dedicated/decentralised waste gas treatment systems for each point source	Reduction of solvent emissions and lower energy consumption with higher removal efficiencies	
	Air seals on the entrance and the exit of the ovens/driers	Reduction of fugitive emissions	
Shaping/sanding/ painting	Air extraction from shaping and painting room processes	Reduction of particulate emissions	✓
	Dry filter systems	Particles removal	
	Electrostatic filter (precipitator)	Particles removal	
	cyclones	Particles removal	✓
	Fabric filter	Particles removal	✓
	Venturi particle separation	Particle separation from air	
	Scrubber	Reduced particulate emissions to air	
Painting	Water-based paints	reduction of VOC emissions	✓
	High solid paints	reduction of VOC emissions	

Table 8.9. Selected BATs for the case study (EC, 2007; Andros, 2016; EC, 2016a)

Stage	BAT	Benefits
General	Ensure the isolation of the different work spaces the more efficient possible, to avoid high air exchange.	Reduce till 90% fugitive VOCs emissions from the glassing/curing room
	Computerized inventory control	No data found
	Solid waste segregation	No data found
Glassing	Store and reuse cleaning solvents	80 - 90 % of cleaning and purge solvent can be recovered for re-use (EC, 2007)
	Cover containers and vats	Till -80% VOC (acetone) emission (EC, 2007)
	Conserve the resin between 18 to 25 grades Celsius.	It allows the resin exploitation till 100% (Andros, 2016)
Resin preparation	Use smaller barrels of resin	It allows the resin exploitation till 100%
	Add a nitro diluent	It allows the resin exploitation till 100% (Andros, 2016)
Glassing/ curing/ painting	Air extraction from coating and drying(curing) processes	Ensure 100% waste air treatment
	UV oxidation	VOCs removal efficiency 95% (EC, 2007)
Shaping/ sanding /Painting	Air extraction from shaping and painting room processes	Ensure 100% waste air treatment
	Cyclones or fabric filter	Particulate removal <70% to 99% (EC, 2007; EC, 2016a)
Painting	Water-based paints	Voc reduction < 80% to 90%. (EC, 2007)

- It is important to note that reusing solvents and covering containers not only reduce the VOCs emission, but indirectly reduces the need of raw material (input).
- Regarding of BAT's general process, they help to improve a correct management of both, the material and waste which can be reduce, although to quantify the effective benefits results rather difficult. The exchange of waste air from a contaminated to an uncontaminated space affects less to the worker health, and the pollutants are not dispersed everywhere make easier its treatment.
- Buying smaller barrels, conserving them in a dry place at the temperature between 18 °C and 25 °C, and using a nitro diluent just in case the resin starts to polymerize (for a maximum of 20% of the resin weight), allows not to waste ruined resin.
- Dust emission can be collected to improve indoor air quality and to avoid the particulates extent the outdoor environment. Thanks to the air extraction system connected with a cyclone or fabric filter air treatment system, the PM quantity could be lowered till 99%. A hypothetical 90% efficiency it can be reach a reduction of dust emission from 193.40 kg to 19.34 kg.
- Covering containers where tools are cleaned is an important good practice to reduce VOCs emissions. Thereby, acetone volatilization could be reduced till 80%. A hypothetical 70% reduction in acetone consumption generates a decrease of VOCs emissions from 203.23 kg to 112.23 kg. It supposes, in addition to environmental benefits, a significant cost reduction for the producer of the surfboards. Furthermore, if replacing the conventional paints, for any water-based ones, its VOCs emissions can be reduced from 80 to 90%. It means an average reduction of emissions from 1.75 kg to 0.26 kg of VOCs per year. It supposes an additional reduction of the total indoor VOCs emissions from 112.23 kg to 110.74 kg. Now, combining this latter practice with the air extraction installation and treatment system in the glassing/curing/ painting rooms, (especially the UV oxidations system) VOCs removal efficiency of 95% can be reached.

Therefore, the VOCs emissions to outdoor almost disappear and the total VOCs emission may turn from 60.71 kg to 5.53 kg.

If the previously selected BATs are adopted, the electricity consumption may increase because of the electric system use for the air treatment and the specific temperature maintenance for the resin conservation. Part of this increase is compensated by a lower use of the vacuum cleaner, due to the collection of the dust directly by the air extraction system, and by a lower cost for the resin purchase. Furthermore, if for each board the pre-shaping is made with the machine the electricity consumption decreases. Anyway, in this chapter the relative energy flows of the new setting in the more sustainable scenario it is not carried out.

8.3.7. Human and ecological impact assessment

This point estimates how much the selected surfboard production job-shop affects the human health and the environment. The improvable configuration is compared with the current one, and thus the results to detect are the more sustainable. The tool used for the Impact Assessment (IA) is USEtox® model. The USEtox model is currently constructed to provide characterization factors (CFs) for human health, freshwater ecological damages, polluting emissions to indoor air, urban and rural air, freshwater and agricultural soil. Combining CFs with emitted mass serves derivation of an Impact Score (IS) for each product of all compounds or product system in a comparative LCA (Life Cycle Assessment) setting. LCA-setting concerns our goal, in fact, the final impact scores are used as input for selecting the preferred product system (scenario). Human health damages include carcinogenic impacts, non-carcinogenic impacts, and total impacts (carcinogenic and non-carcinogenic). Ecological damages addressed in USEtox are freshwater ecotoxicity for a range of aquatic species (Frantke et al., 2017).

The Impact Score is estimated (modelled) using a weighted summation of the releases of pollutants from a product system and characterization factors for the potential damages associated to the Eq. (8.5):

$$IS = \sum_i \sum_x CF_{xi} M_{xi} \quad [\text{Eq. 8.5}]$$

IS is the Impact Score for human toxicity at midpoint level expressed in comparative toxic units (CTUh). IS corresponds to the number of cancer or no-cancer disease cases [cases], and it represents the increase in morbidity in the total human population. At endpoint it is expressed as number of Disability-Adjusted Life Years (DALY), in the total human population. The Impact Score for ecotoxicity is expressed at midpoint level as Potentially Affected Fraction [PAF] of freshwater species integrated over exposed volume and time (PAF m³ d). At endpoint level is expressed as Potentially Disappeared Fraction (PDF) of freshwater species integrated over ex-posed volume and time (PDF m³ d).

CF_{x,i} is the Characterization Factor for the potential toxicity impacts of substance x released to compartment i (cases/kg emitted), CF_{x,i} is for human toxicity impacts (PAF m³ d/kg emitted), for ecotoxicity impacts at midpoint level, the characterization factor for the potential human health damages (DALY/kg emitted) and for potential ecosystem quality damages (PDF m³ d/kg emitted).

M_{x,i} is the emission of substance x to compartment i (kg emitted) (Frantke et al., 2017).

8.3.7.1. Functional unit and system boundaries definition

In order to compare the two configurations of production, the chosen functional unit is: “production of 140 surfboards” because this is the production considered in the previous points

of this chapter (year 2016). The referred board size is the same chosen for the quantitative analysis.

The study system corresponds to manufacturing process for production of surfboards. This process only includes the manufacture of the material for the shape, glassing, curing, painting and packaging of the boards. The importing of the materials and the shipment are not considerate. The perimeters of the system are the plant, it is a gate-to-gate focus. For this, the only emission regarded is the PU foam and polyester resin dust (analysed as PM10), the VOCs (Styrene, acetone, ethyl acetate and xylene) and Polyester dust. Although this emission is indoor to the job-shop (only may affect the inside environment) due to the absence of an air treatment system and an incorrect waste management system, the dust not collected and VOCs could go outdoor if doors are open. On the other hand, the collected PU and Polyester dust is treated like all others generated waste. These wastes are taken out to the mixed or plastic collectors (it was not really defined by the employee), so that it is not excluded that subsequently it disperses when disposed to the landfill. Anyway, for any type of emission to calculate IS, specific assumptions are made regards the environment compartment considered. For this, an approach the more possible consistent with the given information is followed.

8.3.7.2. Impact score of base case scenario

In this point, the impacts caused by the base case production configuration are calculated

8.3.7.2.1. VOCs toxicity

The VOCs previously calculated represent an important undesirable emission. But it is necessary to differentiate between VOCs of styrene, VOCs of acetone and VOCs of solvents contained in the spray cans. Exact composition of VOCs, coming from the use of spray cans was really difficult to know, because each brand makes different product. As reference, the document of the safety data sheet of a Montana94 spray paint can (MTN, 2017) was taken. Between the various chemicals only the Ethyl acetate and Xylene solvents are considered (it has been assumed contributing to the 50% of the total VOC each one), because representing the most of total mix of solvents that is written in the sheet.

The total emission of styrene is 73.48 kg and coming from the entire process. This summarized included VOCs from glassing (excluding come from acetone use), VOCs from curing and VOCs from leash plug installation. For it, the amount of acetone (130 kg) and the relative amount of solvents VOCs in the spray cans (1.75 kg) is known (0.875 kg of ethyl acetate and 0.875 kg of xylene).

Annex A (Table 8.11 and Table 8.12) shows the styrene, acetone, ethyl acetate and xylene characterized in USEtox. The cells of the selected CFs values are in red. The reason which both Occupational indoor air at the indoor scale (occ.airI) and urban air at the urban scale (airU) are considered is due to the lack of an air treatment system. Due to this reason, untreated VOCs reach the outdoor air, so to affect in the peer measure the two emission compartments. The Impact Scores for the VOCs are calculated applying the Eq. (8.5) for Midpoint human toxicity (MHT), Endpoint Human Toxicity (EHT), Midpoint Ecotoxicity (ME) and Endpoint Ecotoxicity (EE). The results for each IS are shown in Table 8.10.

Table 8.10. IS results of the base case and improve scenario

BASE CASE SCENARIO				
	VOCs	PU	Polyester resin	Total
IS _{MHT} (CASES)	6.37E ⁻⁰⁴	¹ 2.34E ⁻⁰⁴	³ 2.48E ⁻⁰³	33.51
IS _{EHT} (DALY)	6.34E ⁻⁰³	² 6.67E ⁻⁰²	0.01	8.30E ⁻⁰²
IS _{ME} (CTUe)	19.30	³ 43.10	³ 33.00	95.40
IS _{EE} (CDUe)	9.66	³ 28.50	³ 16.50	54.66
IMPROVE SCENARIO				
	VOCs	PU	Polyester resin dust	Total
IS _{MHT} (CASES)	6.05E ⁻⁰⁴	¹ 2.30E ⁻⁰⁴	³ 2.45E ⁻⁰³	32.85E ⁻⁰⁴
IS _{EHT} (DALY)	6.02E ⁻⁰³	² 4.02E ⁻⁰²	7.19E ⁻⁰³	5.34E ⁻⁰²
IS _{ME}	14.40 PAF CTUe	³ 38.30 PAF m ³ d	³ 23.10 PAF m ³ d	75.80 PAF m ³ d
IS _{EE}	7.19 PDF CDUe	³ 19.80 PDF m ³ d	³ 11.50 PDF m ³ d	38.49 PDF m ³ d

1. For this IS only the CF of the Ethylene glycol and is amount are not available
2. For this IS are considered CF for the ethylene glycol and PM
3. For this IS the CF of the PM are not available

8.3.7.2.2. Polyurethane dust toxicity

The total PU particulate impact is calculated as the sum of the particulates impact and the impacts of each chemical that stays in the material. According to the bibliography Toluene diisocyanate (TDI) and Ethylene glycol (polyol) are considered constituent in equal amount (50% of TDI and 50% of polyol) in the foam (Kinyanjui et al., 2015).

The total of the PU particulate matter is the sum of the dust coming from the shaping operation and that coming from the fins attachment system (169.51 Kg). The PU dust from the leash plug cup installation is not considered because it is constituted of a mix of polyurethane, wood, and fibre glass. Furthermore, it is a minimum quantity respect to the dust that is from other operations.

Ethylene glycol is characterized as in Annex A (Table 8.11 and Table 8.12). TDI in USEtox is available only for ecotoxicity (data are not given for human toxicity), and is characterized as in Annex A (Table 8.11 and Table 8.12).

For this kind of emission, the same consideration is made than for the VOCs emissions about the compartments receiving the emission. In this case, that only the 50% of the particulate achieve to outdoor air is supposed, whereas the rest 50% stay inside the job-shop till the cleaning operations. There are not data available to estimate the quantity of particulate can escape out of the job-shop. For this, the percentage of 50% is random number.

Regarding CF of the particulate matter of the dust, USEtox model does not provide data about any PM size. In this chapter the CF used for the characterization of PU dust is found in the bibliography (Van Zelm et al., 2008), referred to PM₁₀ (size in which most probably it falls into) and it is only expressed as DALY/kg emitted. For this reason, the only characterization is at the endpoint.

The Endpoint Human Toxicity Potential expressed in Comparative Damage Units per kg [CDU_h·kgemitted⁻¹] = [DALY·kgemitted⁻¹] is 2.6×10^{-4} . The Impact Score for the PU particulate emission are shown in Table 8.10.

8.3.7.2.3. Polyester resin dust toxicity

A real patent is taken as reference to know the chemicals which take part of the reaction in the process of resin production (Watanabe et al., 1975). In order to make easier the calculation, each chemical participating of peer measure in the formation of resin (reality it is not too much different to this scenario) and it represents the remain 64% weight of the resin (36% weight is styrene). So, in the case of the dust coming from the sanding, 23.80 kg, every chemical

(propylene glycol, maleic anhydride, dimethyl terephthalate and ethylene glycol) contributes with 16% of the weight, 3.8 kg.

The CFs for styrene, ethylene glycol and PM are shown in Annex A (Table 8.11 and Table 8.12), but in this case the outdoor compartment receive only the 50% of the total emissions, for the same reason explained for the PU dust.

Propylene glycol, Dimethyl terephthalate, Maleic anhydride are characterized in USEtox as in Annex A (Table 8.11 and Table 8.12). The Impact Score for the Polyester resin particulate emission are shown in Table 8.10.

8.3.7.2.4. *Total impact score*

The total Impact Score of the emissions in the actual job-shop production is calculated as the sum of all IS for each type of emission. Anyway, conserving the specificity of each IS. The total Impact Score are shown in Table 8.10.

8.3.7.3. Impact score of the improved scenario

The improved scenario is a new configuration in the production process that make it less environmentally and healthy impacting. The impact score is calculated in this section, but considering the data of the emissions resulting after applying the selected Best Available Techniques.

8.3.7.3.1. *VOCs toxicity*

The Impact Scores of VOCs are shown in Table 8.10. The method of calculation of VOCs impact is the same of the VOCs in the base case scenario.

- The emission of Acetone is reduced at 39 Kg.
- The emissions of ethyl acetate and xylene are 0.13 kg each one.
- The emission in the urban air compartment are reduced of the 95% for each substance.

8.3.7.3.2. *Polyurethane and polyester dust toxicity*

The method of calculation for PU particulate and polyester emissions is the same already used in the base case scenario. This case needs to discount the emission to the outdoor air for the extraction and the treatment of the waste air that it is supposed reach a 90% of efficiency. So, the Impact Score for the PU particulate and polyester emission are shown in Table 8.10.

8.3.7.3.3. *New total impact score*

The new total Impact Score of the emissions in the improved scenario of production is calculated as the sum of all new IS for each type of emission. Anyway, conserving the specificity of each IS. The total Impact Score are shown in Table 8.10.

8.3.7.4. Results and comparison between the conventional configuration and the new scenario

The results of total IS obtained in the base case scenario and improved scenario are discuss and compared to evidence the variation on the human and ecotoxicological impacts (Figure 8.8 and Figure 8.9). This is due to change on the base process configuration (base case scenario) after the adoption of the BATs. The new trial configuration appears as “Improved Scenario”.

Human toxicity at the midpoint level appears remaining at the same value which it may seem not to be an important reduction in the improved scenario.

Finally, for a correct interpretation, it is necessary to take account that in the calculation of the midpoint human toxicity, the CF for PM was provided neither by USEtox nor by the

bibliography. Furthermore, to the midpoint impact of the PU dust only the Ethylene glycol contributes. If all the CFs were available, it is very probable that the reduction of the impact in the improvable scenario would be more important. In fact, thanks to the selected BAT for the PM and VOC emission reduction and streams treatment, exposure to these pollutants is reduced.

Regarding the endpoint human toxicity, the gap between the impacts of the relative scenarios is more accentuated. The reason of this is the major availability of the pollutants CFs data that make the results more reliable. Anyway, the IS values remaining in the same order of magnitude.

Figure 8.8 reflects fully the intrinsic deficiency to the IS estimation due to the unavailability of all the CFs. In fact, IS values for human toxicity at endpoint level are significantly higher than those for the midpoint level. Probably in CFs of all substances, the situation is reversed and the IS at midpoint are higher than the IS at endpoint level. Surely always keeping the values of the IS of the improved scenario lower than the others.

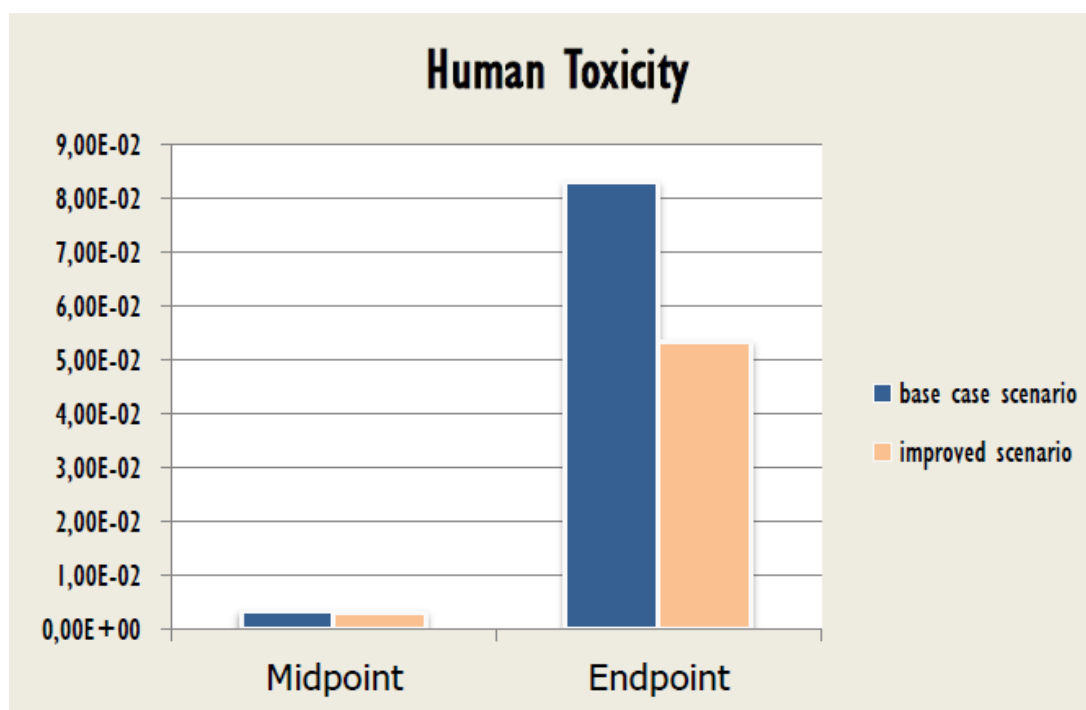


Figure 8.8. Impact Scores of Human Toxicity: Midpoint Human Toxicity and Endpoint Human toxicity

Ecotoxicity (only for fresh water) shows a clear difference between the IS values of the two scenarios. At the midpoint level the improved scenario is more than 25 CTUe down of the conventional scenario, whereas at the endpoint level the difference is about of 20 CTUe. Even if also for the Figure 8.9 it is considered a grade of uncertain that could modify the real results. In this case the absence of the CFs is for the two types of toxicity, and thus they are affected at the same way. However, the values do not include the PM CFs, for both midpoint and endpoint toxicity.

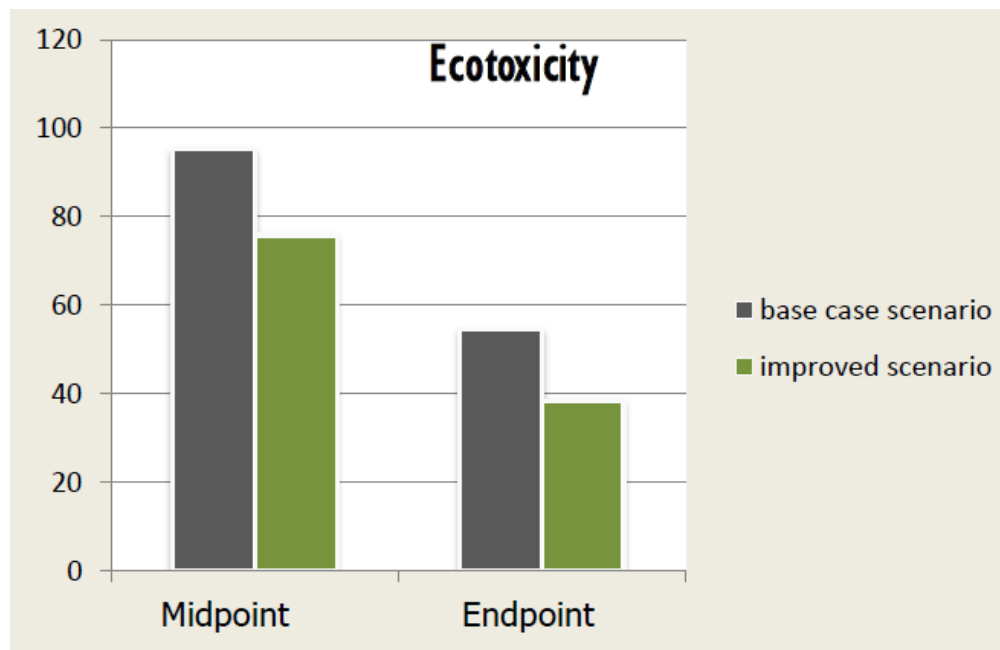


Figure 8.9. Score of Ecotoxicity: Midpoint ecotoxicity and Endpoint ecotoxicity

Comparing Figure 8.8 and Figure 8.9 is observed that the ecosystem is affected by this activity. A higher vulnerability to the pollutant generated from the job-shop analysed is demonstrated. In both cases, the impacts are reduced by the improvable scenario.

Finally keeping in mind, the existence of a grade of uncertain of the results, the application of BATs has permitted to reduce the amount of material and his relative emissions. Because of this, the relief of the impact is unavoidable.

8.4. DISCUSSION AND RESULTS

Directive 96/61/EC, of July 1, on Integrated Prevention and Control of Pollution (IPPC Law), define, among others, the concept of Best Available Techniques (BAT) (PRTR, 2019). Although, this small installation of surfboards is not affected by the IPPC, the methodology applied includes the BAT Analysis. This methodology presented, combines three tools based on life cycle thinking: the MEFA, the BAT analysis, and the Impact Assessment.

The addition of Impact Assessment to existent methodology permits quantify and evaluate the magnitude and significance of the potential environmental impacts of a product system (Laurin and Dhaliwal, 2017). According to the results of MEFA, six stages have been proved to be improvable, because of their high resources consumption or emissions (Table 8.7). According to ten IFs identified in the process and the BAT inventory, fifteen BAT (Table.8.8) were selected in order to reduce the effects of them.

STAN is the selected software to identify the ten IF (seven related with materials and three concerning energy stream). Three IF have been selected for the shaping operation, one for resin preparation, three for glassing, and one for sanding, painting and waste stages.

The application of BAT analysis provided an inventory of sixty-nine techniques candidates to be BAT for the analysed job-shop. According to the identified IF in the process and the BAT inventory, fifteen BATs were selected in order to reduce the effects of the ten IF. Even if not all identified IF are reduced, the adoption of these BATs to the process will provide the optimal alternative. The major material saving comes from BAT, which allows the resin not to be damaged with time. VOCs emissions may be reduced in the indoor air applying a BAT that

help to not evaporate the acetone. VOCs emission to the outdoor air may be almost eliminated applying the BAT that permits to treat the outgoing stream.

The Impact Assessment analyses how the surfboards manufacturing process affects both to the human health and ecosystems. In this case, IA studies two systems: the job-shop studied and the improved system with BATs implanted, comparing the Impact Score of both systems. For this, IA calculates IS that is Impact Score.

IS is estimated using Eq. (8.5). To human health IS is expressed in CTUh. At midpoint level represent the increase in morbidity in the total human population and at endpoint level, represent a number of Disability-Adjusted Life Years. On other hand, to ecotoxicity is expressed in PAF, at midpoint level as potentially affected fraction of freshwater species. At endpoint level is expressed as potentially disappeared fraction of freshwater species, both integrated over exposed volume and time.

The results of the IA are shown in Figure 8.8 and Figure 8.9. As expected, even so with the great uncertainty of the FCs, the application of the BAT in an improved system, allows to reduce the amount of material and emissions reducing the impact.

This chapter has a great importance in the marine equipment production. This is because the surfboards job-shop can be a simplification of boat making. The reason is that currently, the compound used for surfboards (FRP) has been used in small boats, because of its advantages such as light weight, low fuel consumption, high speed, excellent economic, good manufacturability and low corrosion and become one of the tendencies of development for energy saving and environmentally friendly vessels (Kai et al., 2018).

On other hand, as indicated in the 2015 action plan (EC, 2015b, 2015c) that European Commission adopts to boost the circular economy. The circular economy begins from the beginning of the life of a product. Both the design phase and the production processes have an impact on obtaining, using resources and generating waste during the life of a product. This chapter is focus in a production process, using concepts as BAT (that appears in 1996 to potentially contaminating installations, currently under the framework of industrial emissions legislation (EU, 2010a)). This concept, along with others as Best Business Management Practices (which appear under the EMAS regulation (EU, 2017)) can be incorporated in the productive process its life cycle. Trying to incorporate criteria of circular economy in order to increase efficiency, extend the life cycle, and improve the efficiency in recycling. With the incorporation of BAT, the aim is to increase the sustainability of the system, reducing the consumption of products in the process, or of consumption of energy. Establishing a study of the system to the product eco-design.

8.5. CONCLUSIONS

This paper presents a methodology intended to use sustainable indicators and the LCT focus into a job-shop production process. The methodology combines three tools: the MEFA, the BAT analysis, and the Impact Analysis. The methodology has been validated in a small surfboards production job-shop. Ten Improvable Flows have been identified for the process; consequently, fifteen candidates BAT have been proposed aiming to act upon these flows. The combination of MEFA and BAT analysis has confirmed to be a very good option for process evaluation considering sustainability criteria.

The use of USEtox model has permitted to compare the base case scenario with the improved one in the basis of toxicity impact. The Excel spreadsheet resulted of easy use although the large quantity of data presented. The results achieved with the calculation of the IS relative to the two scenarios from the CFs of USEtox, demonstrate consistency with the

expected results, and show the reduction of the impacts after the application of the selected BATs.

This methodology has turned out to be applicable also to a job-shop that apparently does not seem have impacts because of its restricted and simple industrial metabolism. On the one hand MEFA obtains deep information about the environmental aspects of the process can be extracted to identify the IF (whether they are inputs, outputs or internal flows). On the other hand, BAT analysis and its adoption, which helps in considering not only environmental aspects but also economical that may affect the selection of techniques, the environmental performance can be improved, and this job-shop may be transformed into a “low impact” plant.

These results are very useful to enhance the process efficiency. Resources consumption, waste and emissions generation are reduced, and, at lower level, economical aspects are considered to not affect them. Due to these reasons the work is endorsed to fall within the Circular Economy model. Finally, this chapter can be applied to a manufacturing of marine equipment that use the same material and amplifying the system to a large industry.

8.6. ANNEX A

Table 8.11. Characterization Factors in USEtox expressed in Comparative Toxic Units per kg

		Styrene		Acetone		Ethyl acetate		Xylene	
		Occ. airI	airU	Occ. airI	airU	Occ. airI	airU	Occ. airI	airU
Midpoint	cancer	6.43E-06	7.12E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.90E-08	6.36E-09
Human	non-cancer	1.29 E-06	1.42E-07	3.87E-08	6.03E-09	3.84E-08	5.75E-09	1.14E-06	1.48E-07
Toxicity	total	7.71E-06	8.55E-07	3.87E-08	6.03E-09	3.84E-08	5.75E-09	1.19E-06	1.54E-07
Endpoint	cancer	7.39E-05	8.19E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.64E-07	7.31E-08
Human	non-cancer	3.47E-06	3.85E-07	1.04E-07	1.63E-08	1.04E-07	1.55E-08	3.08E-06	3.99E-07
Toxicity	total	7.74E-05	8.58E-06	1.04E-07	1.63E-08	1.04E-07	1.55E-08	3.64E-06	4.72E-07
Midpoint Ecotoxicity	freshwater ecosystems	4.08E-02	4.68E-02	4.87E-02	4.88E-02	9.98E-02	9.99E-02	1.74E-02	1.84E-02
Endpoint Ecotoxicity	freshwater ecosystems	2.04E-02	2.34E-02	2.44E-02	2.44E-02	4.99E-02	5.00E-02	8.71E-03	9.18E-03

[CTUh·kgemitted-1] = [cases·kgemitted-1] for the Midpoint Human Toxicity

[CDUh·kgemitted-1] = [DALY·kgemitted-1] for the Endpoint Human Toxicity

[CTUe·kgemitted-1] = [PAF·m3·d·kgemitted-1] for the Midpoint Ecotoxicity

[CDUe·kgemitted-1] = [PDF·m3·d·kgemitted-1] for the Endpoint Ecotoxicity

Table 8.12. Characterization Factors in USEtox expressed in Comparative Toxic Units per kg

		Ethylene glycol		TDI		Propylene glycol		Dimethyl terephthalate		Maleic anhydride	
		Occ. airI	airU	Occ. airI	airU	Occ. airI	airU	Occ. airI	airU	Occ. airI	airU
Midpoint	cancer	0.00E+00	0.00E+00	-	-	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human	non-cancer	9.63E-08	2.25E-08	-	-	6.86E-08	9.71E-09	5.60E-07	9.03E-08	1.76E-06	2.86E-07
Toxicity	total	9.63E-08	2.25E-08	-	-	6.86E-08	9.71E-09	5.60E-07	9.03E-08	1.76E-06	2.86E-07
Endpoint	cancer	0.00E+00	0.00E+00	-	-	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Human	non-cancer	2.60E-07	6.08E-08	-	-	1.85E-07	2.62E-08	1.51E-06	2.44E-07	4.74E-06	7.74E-07
Toxicity	total	2.60E-07	6.08E-08	-	-	1.85E-07	2.62E-08	1.51E-06	2.44E-07	4.74E-06	7.74E-07

Midpoint Ecotoxicity	freshwater ecosystems	1.22E-01	1.25E-01	3.23E-01	3.29E-01	8.85E-02	9.24E-02	3.80E+00	3.81E+00	1.68E+00	1.69E+00
Endpoint Ecotoxicity	freshwater ecosystems	6.11E-02	6.24E-02	1.62E-01	1.64E-01	4.43E-02	4.62E-02	1.90E+00	1.91E+00	8.39E-01	8.46E-01

[CTUh·kgemitted-1] = [cases·kgemitted-1] for the Midpoint Human Toxicity

[CDUh·kgemitted-1] = [DALY·kgemitted-1] for the Endpoint Human Toxicity

[CTUe·kgemitted-1] = [PAF·m3·d·kgemitted-1] for the Midpoint Ecotoxicity

[CDUe·kgemitted-1] = [PDF·m3·d·kgemitted-1] for the Endpoint Ecotoxicity

CHAPTER 9. SOURCES, SINKS AND TRANSFORMATIONS OF PLASTICS IN OUR OCEANS: REVIEW, MANAGEMENT STRATEGIES AND MODELLING

This chapter is a reproduction of the following publication derived from the research carried out by the doctoral student during the training stage:

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SUMMARY

Currently, 60-80% of litter is plastic, and almost 10% ends up in the ocean directly or indirectly. Plastics often suffer from photooxidation producing microplastics and these microplastics derived from the breakdown of larger plastics are called secondary microplastics. These compounds simply cannot be extracted from the oceans, and once mixed, they enter the food chain and may have toxic effects. Figure 9.1 sum up the different land and sea sources reaching different sinks.

This chapter reviews the current existing information on the topic in the scientific literature. Then, the current plastic management strategies in the marine environment are analysed, with the objective of identifying possible needs and improvements from a sustainable point of view, and to define new approaches. Simultaneously, a material flows analysis in different media of the marine environment is carried out using system dynamics. A preliminary model of plastics mobilization into the ocean to other media of the marine environment (like sediments and biota) is developed and validated with the existing data from the previous steps of the work.

This chapter expands the current knowledge on the plastics management, their transformations and accumulation in the marine environment and the harmful effects on it. Likewise, preliminary dynamic model of mobilization of plastics in the ocean is implemented, run, and validated. The developed model can be used to predict trends in the distribution of the plastics in the ocean with time. In addition, the most important reservoirs of plastics in the ocean can be observed. Although plastics undergo transformations in the marine environment, it is not a means of disposal since most of them are non-biodegradable. Most plastics accumulate on the seabed. The proportion of microplastics found in sediments is higher than that of macroplastics.

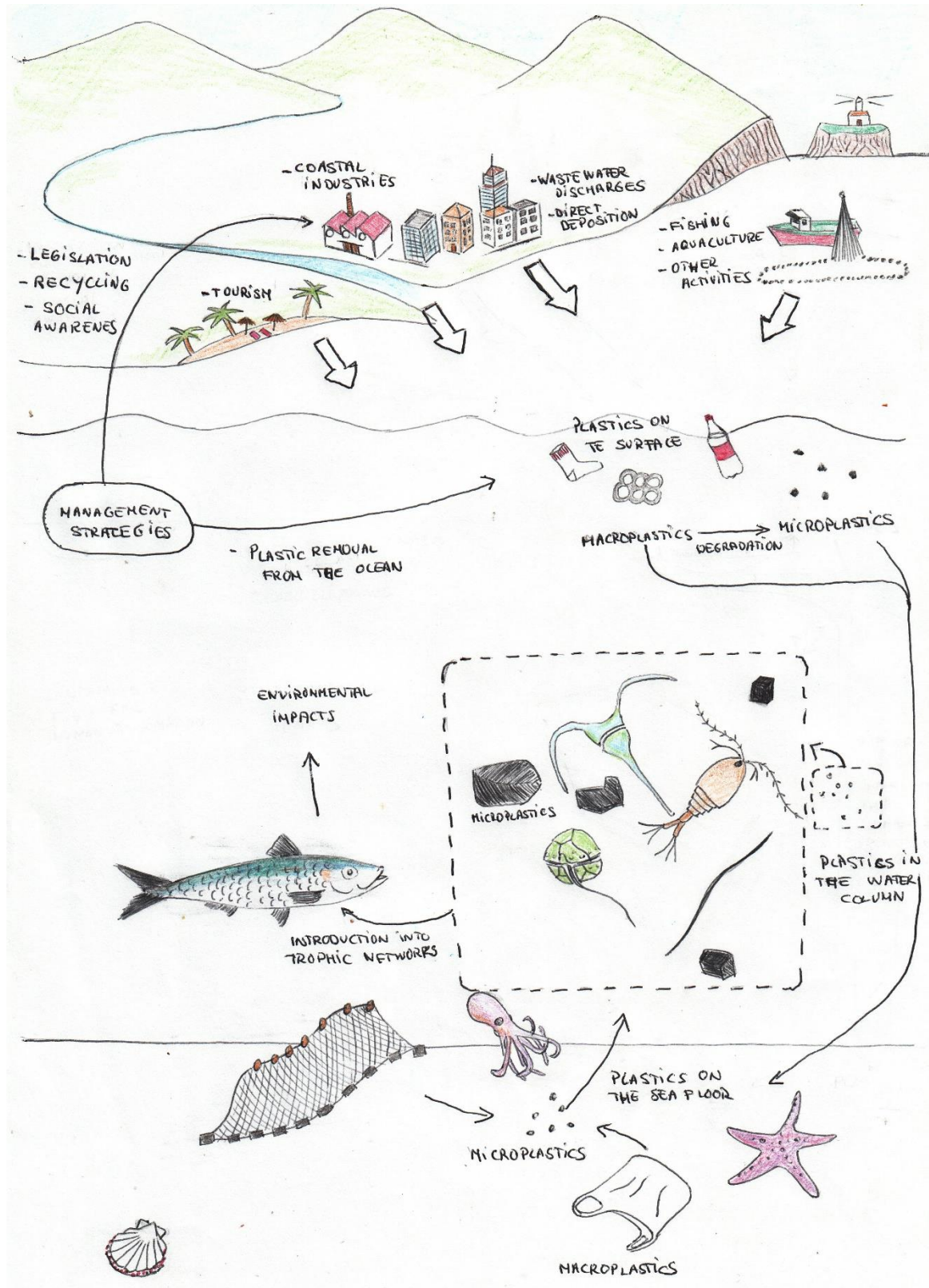


Figure 9.1. Sum up of sources and sinks (Own elaboration)

9.1. INTRODUCTION

Plastic is a term that refers to a group of synthetic polymers (UNEP, 2015), and most of them are of petrochemical origin and derive from the polymerization of monomers (Wayman and Nieman, 2021). Polymers are originated by different transformations of raw materials which 99% come from fossil materials (crude oil or natural gas) (Nielsen et al. 2019; Petrochemicals Europe, 2019; ISO, 2020).

Plastics can have many classifications attending to different approaches. Resin Identification Coding System (RIC) is an international classification system based on its composition. RIC classifies plastics into seven categories: polyethylene terephthalate (PET or PETE), high density polyethylene (HDPE), polyvinylchloride (PVC), low density polyethylene (LDPE), polypropylene (PP), polystyrene (PS) and others (O). The last ones are nylon fibres, feeding bottles, compact discs, containers for medical use, car parts, etc. (ASTM, 2021).

Other classification can be attending to the size. Plastics with a size >25 mm are "macroplastics", "mesoplastics" have a size between 5 and 25 mm (Romeo et al., 2015). "Microplastics" correspond to plastics of less than 5 mm. Some authors also add "nanoplastics", a term under debate that has set the upper size limit at either 1000 nm or 100 nm (Gigault et al., 2018). To finalize the classification, microplastics according to their origin can be primary or secondary (Cole et al., 2011). Primary microplastics are those that add new micro-sized plastic material to the environment (Wang et al., 2019) and come from activities such as: medical applications, consumer products, agriculture, indoor particulate emissions, urban and transport infrastructure, intentional shredding and fragmentation plastic, processing industry, handling during manufacturing or maintenance (factories), abrasive media used at sea or coastal zone, coating or maintenance of plastic painted surfaces at shipyards or at sea or maritime sector (UNEP and GRID-Arendal, 2016). Secondary microplastics originate from the fragmentation of the macroplastics garbage in the environment (Wang et al., 2019).

After the 1950s, the use of plastic began to increase dramatically, due to its benefits for the health, safety, and energy of society (Schmaltz et al., 2020). In that moment the world had 2500 million people and the world production of plastic was 1.5 tonnes (Aytan et al., 2020). Since 2004, as Figure 9.22 shows, plastic production has increased considerably. The increase of plastic production since 2004 was from 225 million tonnes to 367 million tonnes in 2020 (Plastics Europe, 2022) and from 2012 plastic production increases 4% annually (Jambeck et al., 2015; García-Rivera, et al., 2017). The huge global production of plastics and its current great demand makes many scientists call our time as the "age of plastics" (Avio et al., 2017; Paiu et al, 2020).

Plastics are used from the automotive industry, packaging, and food to leisure, increasing the consumer dependence. Consequently, the demand for plastic products currently grows annually (Al-Salem, 2019). Loss of material value because of single use and low recycling rates, ill-effects on nature like climate and human health, are some of the problems of plastics (European Parliament, 2019). In 2014, the United Nations Environment Program (UNEP) identified plastic pollution as one of the top 10 emerging global environmental problems (Peng et al., 2020). It is estimated that plastic pollution causes \$13 billion of financial damage annually (Nielsen et al., 2019). This is a big threat to marine and terrestrial ecosystems globally (Derraik, 2002), but nowadays, the focus is on marine pollution. According to Jambeck et al (2015) in their Top 20, China, Indonesia and the Philippines are the countries that generate the most plastic marine debris.

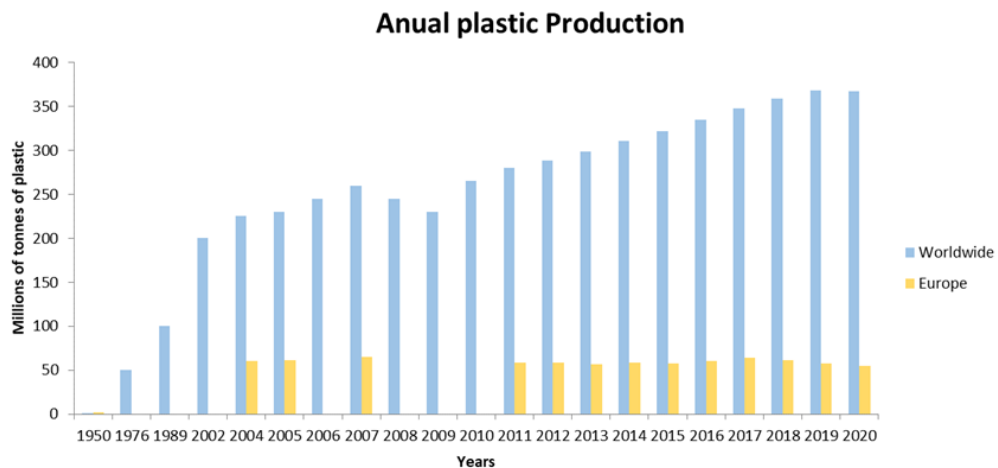


Figure 9.2. Types of different plastic waste produced worldwide in 2015 (Own elaboration, data source: National Geographic, 2018)

Marine litter is a result of complicated waste management problems (Ahmad-Kamil, 2022) and it affects all the oceans of the Planet, from surface to seafloor, appearing in places as remote as the Arctic or the Antarctica (Scotti et al, 2021, Parker, 2018). Parker (2018) used the map of Jason Treat drawing the distribution of marine plastic worldwide, the large accumulations of these materials, and the main rivers and land sources that transport these compounds to the sea. Marine litter composition can be made of infinity materials, although plastic is the more visual material due to its floatability (Velis et al, 2014) and colours. Plastic litter has always been recorded to be the most abundant marine litter compared with other types of marine litter (Galgani et al 2015; Aytan et al, 2020; Ahmad-Kamil, 2022). Plastics are important due to its daily use and functionality because it is the most versatile material of modern times (Plastics Europe, 2022). Being cheap, lightweight, corrosion-resistant, elastic, and durable (Chen, et al.; 2021).

Regarding of marine litter composition, Galgani et al (2015) affirmed that containers, fishing nets and their little parts, as well as small unidentifiable pieces of plastic represent the largest waste in marine litter, being the 80% from land and 20% from ocean-based activities (Schneider et al, 2022). Furthermore, these plastics are classifying into three categories: plastics of fishing gear (27%), single-use plastics (49%) and other plastics (6%) (European Parliament, 2021).

The objective of this chapter is to contribute to the knowledge of both plastic waste sources and plastics sinks in the ocean, plastics and microplastics transformations, and needs to the waste plastic management strategies, through a systematic bibliographic review and analysis. System dynamics is used to develop a dynamic material flow analysis, by the implementation of a preliminary multimedia modelling of plastics mobilization into the ocean to other media of the marine environment. This will be useful to predict trends and to identify new areas of study related to plastic waste accumulation in the oceans.

9.2. METHODOLOGY

In this chapter, the applied methodology analyses the current problem of marine plastics. It consists of research work that analyses the background and state-of-art for marine plastics and the development of a model about the mobilization of the plastics in the ocean.

- To analyse the current problem of marine plastics, this chapter applies research, systematic review and analysis, identifying topics in the field, and classifying the works into them.
- Due to the dynamic nature of our system, system dynamics is used for studying and managing complex system which change over time, as a method of analysing problems in which time is an important factor. The dynamic problem studied is the accumulation of plastics in the marine environment: once plastics enters to the ocean, they distribute in different media. Multimedia dynamic modelling is developed implementing four model's phases increasing gradually the complexity. Models are used to predict trends of the system behaviour in a dynamic focus.

9.2.1. Review and study of the real system

- Plastic marine litter review. Deep systematic research of literature is carried out to analyse how the problematic of plastic waste in the oceans is being addressed. In addition, this review provides an insight into the latest studies on this subject are focusing on. It is also used to collect data needed for research.
- Management strategies analysis. An analysis of current marine plastics management strategies is developed, considering the information from the review.
- Sources, sinks and transformations in the ocean. A small study to determine the origin of plastics, microplastics and the main sources and sinks in the oceans is done, considering the information obtained from the review. The transformations that these polymers undergo in the marine environment are also analysed.

9.2.2. Modelling of the plastics fate in ocean

After a previous deep review and analysis of existing models a preliminary model with four phases of the mobilization of plastics through ocean media (water, sediment and biota) are developed, focused on system dynamics using dynamic modelling. Models are used to analyse different scenarios obtaining the fate of the plastics (including macro and microplastics) in the ocean.

9.3. REVIEW AND STUDY OF THE REAL SYSTEM

An extensive review of scientific papers is carried out to identify those related to marine plastic waste, as well as its management strategies, or sources, sinks and transformations in the ocean.

The search is carried out using Web Of Science (WOS) database of the Spanish Foundation for Science and Technology (FECYT) under the Ministry of Science and Innovation. The searches were made selecting "all years (1900-2022)" in WOS to search all existing articles to date.

9.3.1. Plastic Marine Litter Review

To review plastic marine litter, three searches with different initial parameters were performed. To the first search "marine litter" and "plastics" were used as a TITLE. In this search one of them was removed because it was a correction from another paper. To the second search "marine litter" as TOPIC and "plastics" as TITLE were used. In the second search also was remove another paper because of the topic does not correspond to the case study. The last search was "marine litter" as TITLE and "plastics" as TOPIC. After removing overlaps, there were a total of nine hundred and seventy-eight scientist papers in the database of Web of Science about Plastic Marine Litter.

The collected articles were classified into seven categories selected by different topics. Note that an article can belong to different categories dealing with various topics. The

categories are: “macroplastics/mesoplastics”, “microplastics/nanoplastics”, “marine biodiversity”, “management”, “monitoring and modelling”, “policy/social” and “spatial distribution”. “Macroplastics/mesoplastics” group papers talking about large plastics in general, plastics that are over than 5 mm. “Microplastics/nanoplastics” group focus on studies about smaller plastic particles, less than 5 mm. The third category, “marine biodiversity” includes papers about the impact of macro and microplastics in different ecosystems or marine species. “Management” category contains articles of plastic waste management. “Monitoring and modelling” group includes papers that use monitoring and/or a model in its development. “Policy/social” is a category which includes social or political measures such as surveys, prevention programs or legislation. Finally, “spatial distribution” refers to spatial distribution of plastics in the oceans. Figure 9.3, shows the articles per category and the relation between them.

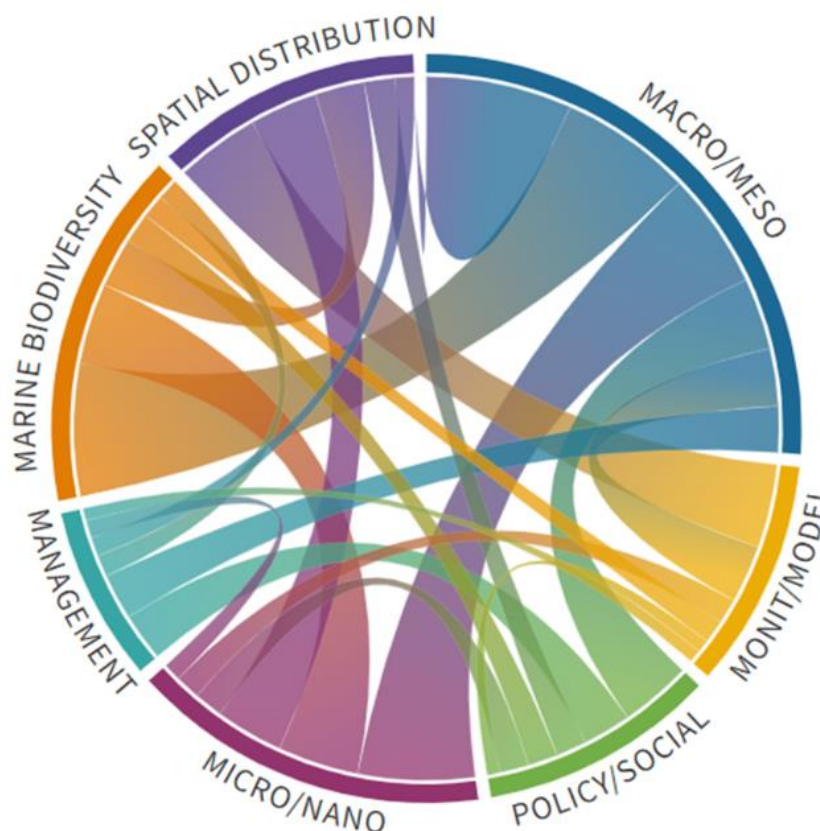


Figure 9.3. Classification of articles in plastic marine litter review (own elaboration)

The first study searched about the presence of marine plastics dates in 1978, based on observations made between 1972 and 1976 on beaches around New Zealand. The main concern in this study is virgin materials (Murray, 1978). Later, other authors as Winston J.E on 1982 studies species that live in marine plastics moving through the oceans. Merrel (1980, 1984) published also the first works about plastic litter in Alaska.

Of the nine hundred and seventy-eight papers analysed, five hundred and eight mention “macroplastics/mesoplastics” because many of them deal with marine litter in general and focus on large plastics, talking also about “microplastics or nanoplastics”. The “microplastics/nanoplastics” include two hundred and sixty-four articles. Three hundred and

seventy-three papers talk about the impact of plastics in “marine biodiversity” and a lot of them talk about plastic ingestion or entanglement in different species: sea turtles, seabirds (in special the genre *Fulmarus*).

Papers about “management” and, “monitoring and modelling” have increased in the last year, one hundred and forty-nine and two hundred and sixty-seven respectively.

In the category “policy/social”, there are two hundred and thirty-one papers that deal with citizen science, environmental education, and projects on surveys on marine litter and beach cleaning. Note that most political-social papers are focused on European politics being the marine strategy framework directive (Directive (UE) 2017/845/EC; Directive 2008/56/EC) one of the most important.

Finally, in the last category, “spatial distribution”, three hundred and seventy-five papers are found. These papers focus on the distribution of plastics in the different oceans and seas of the earth. There are many studies about the composition and distribution of plastic litter in the Mediterranean Sea and its internal seas such as Adriatic.

9.3.2. Management strategies

The category “management strategies” represents 15 % of the papers found in the review (one hundred and forty-nine papers). Although most of them do not specifically deal with marine plastic management, there are papers about management measures on land to prevent their arrival in the marine environment. While management strategies are essential to deal with the problem of plastic mismanagement, it is remarkable that it is the topic on which the fewest articles have been found.

Most of the articles related to the management of plastic in the oceans are reviews of the tools and legal frameworks that contribute to reducing the amount of plastic in the oceans. Although the first reports that deal with marine litter problems date back at the end of the 1960s, it was at 70-80s when most marine ecosystem threats were identified and the first policies were established (Ryan, 2015). Global policies are very necessary to reduce the production and consumption of plastic (especially single-use plastics) (Rangel-Buitrago et al, 2022). Currently, to address marine pollution problems, among other, there are three main international agreements: United Nations Convention on the Law of the Sea (UNCLOS), the International Convention for the Prevention of Marine Pollution (MARPOL) and the Convention for the Prevention of Marine Pollution by Dumping of Waste and Other Matter 1972 (London Convention) (Hsing-Hao Wu, 2022). In addition, at the fifth United Nations Environment Assembly (UNEA-5.1) in 2021, the insufficiency of existing legal frameworks and international policies was insisted on due to the transboundary characteristics of plastics, supported by at least 40 countries (Sun et al, 2021). National policies are widespread throughout Europe based on the European Marine Strategy Framework Directive 2008/56/EC and modified by Directive (EU) 2017/845, where all member states should have achieved Good Environmental Status by 2020 (MITECO, 2022). In Africa, Asia and Oceania they are increasing, in North America they are limited and they are seriously lacking in South America (Frantzi et al, 2021).

Regarding other management techniques such as standard recycling based on mechanical reuse and recomposition, it is a technically inefficient and economically unfavourable method. Marine plastic debris is mixed, embedded with organic matter and contaminated with salts (Faussone et al, 2021). Still, there are works such as that of Veksha et al (2022) investigated the technical and environmental aspects of marine plastic waste treatment, including the separation of PET for subsequent recycling. Faussone et al (2021) tries to make diesel for boats from plastics found in the sea or Liu et al (2022), who uses the calorific value of plastics found in the sea to fire ceramics in a mobile kiln installed in a boat.

Although there is no notification of many strategies to manipulate plastic in the oceans, there are projects such as Clean Atlantic (ongoing European project, whose purpose is to contribute to the reduction of the presence of marine litter in the Atlantic Ocean) (Interreg Atlantic Area, 2020). Ocean Cleanup is other project which is credited with building a giant plastic collection barrier in the ocean, and which works successfully in the Pacific Ocean (The ocean clean up, 2021). Citizen science campaigns are more present, such as the Spanish project about floating marine litter management *Libera, unidos contra la naturaleza* (Proyecto Libera, 2020). There are also projects such as the recent approved "Plastics monitoRIng detectiOn RemedIaTion recovery (PRIORITY)" (COST, 2021), a research network focused on developing, implementing and consolidating strategies to address the global challenge of environmental contamination by micro and nanoplastics.

9.3.3. Sources, sinks and transformations in the ocean

9.3.3.1. Plastic waste sources

The research to date reveals a large disparity between estimates of land-sources plastic debris entering the ocean and the amount of marine debris floating on the ocean surface (Ruiz et al, 2022). In 1975 the annual flow of litter of all materials (no data on plastic waste yet) to the ocean was 6.4 million tonnes (Jambeck et al., 2015). Nowadays exist an increase of data estimates, but even so there are no exact evidence of the quantity and origin of plastics present in the oceans (Jambeck et al., 2015). Currently, studies as Sherrington (2016) estimate 12.2 million tonnes of plastic per year that entering in marine environment. Furthermore, in other studies state that almost 10% of annual plastic production ends up in the oceans from various sources (Avio et al., 2017). Although in more recent studies Ritchie & Roser (2018), have estimated that 8 million tonnes of plastic entered the ocean in 2010 (3% of the annual production of plastics that year). Other works show that in 2015 in the oceans there were 15-51 trillion pieces of plastic (93,000-236,000 tonnes of plastic) (Peng et al., 2020). According to Peng et al (2020) in 2017, the amount of plastic in oceans was more than 33 times of the total accumulated in 2015. In addition, Frantzi et al (2021) ensures that in 2050 there will be 33 billion tonnes of plastic in the ocean. Jambeck et al (2015) estimated that in 2010, 192 coastal countries generated 275 million tons of plastic waste and between 4.8 and 12.7 million tons ended in the ocean. In addition, in their work estimated that at fifty miles from the coast, 99.5 million tonnes of waste plastic were generated, ending up to the ocean between 1.7 and 4.6% in 2010. This data is understandable knowing that almost half of the population of the land resides in the fifty miles of the coast (Cole et al., 2011).

There are a lot of input sources of litter and plastics direct or indirect into the ocean (Figure 9.4). The two main sources are: land sources (more than 80% of the annual inputs) (Ryan et al., 2009; Sherrington, 2016), and ocean sources that are estimated a 20% (Wootton et al, 2022). Land sources inputs can be coastal or inland and the most important are runoff from rivers, wastewater systems/sewerage, wind-blown litter and litter left in beaches (Ryan et al., 2009; Sherrington, 2016; Peng et al., 2020). Plastic particles can draw into the ocean from rivers because of a density lower or like water density (Peng et al., 2020). Sherrington (2016) estimates a mid-point of 0.5 million tonnes of plastics per year that come from rivers.

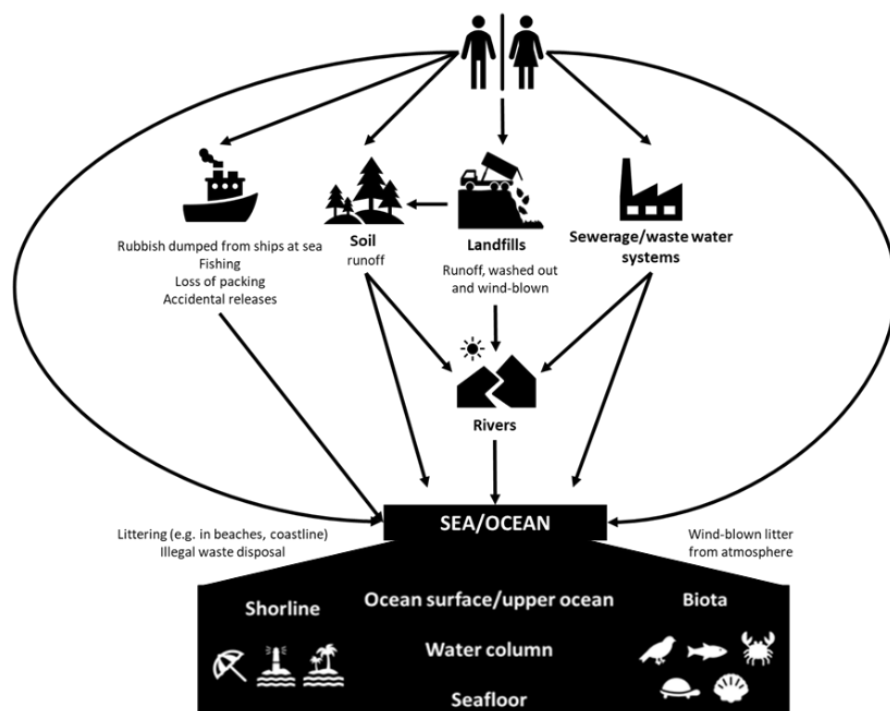


Figure 9.4. Diagram of plastic waste source to the ocean and waste sink in the ocean (own elaboration)

Rubbish dumped from ships, vessels and platforms, loss of packing and accidental releases is another important source of plastic pollution in the seas, and it represents 20% (Li et al., 2016). Other important plastic source is fishing representing between 10-15% of global marine litter by volume (Sherrington, 2016; UNEP and GRID-Arendal, 2016). Marine vessels during the 1970s dumped over 23,000 tonnes of plastic packaging materials (Cole et al., 2011). Nowadays, 640,000 tonnes of discarded fishing gear are added to ocean every year (Li et al., 2016). Currently an average of 1.75 million tonnes per year of litter from at-sea sources is estimated (assumption that 55% by weight is plastic). Fishing and shipping dump 1.15 and 0.6 million tonnes of marine litter per year respectively (Sherrington, 2016).

Sources of microplastics and macroplastics to ocean are almost the same. Microplastics can enter to waterways through domestic or industrial drainage systems and wastewater treatment plants, straining through the filtration systems most of them (Cole et al., 2011). Sherrington (2016) estimates an average input of 0.95 million tonnes per year of primary microplastics to the ocean. The land sources of microplastics contribute 98% in this input and the remaining 2% come from ocean activities (Peng et al., 2020), while the macroplastics input to ocean from land sources is 80% (Sherrington, 2016). Sherrington (2016) also groups the seven products that most contribute to the appearance of microplastics in the oceans: the vehicle tyre dust, pellet spills, textiles, building paints, road paints, cosmetics and marine paint.

Microplastics sources can be classified into sectors: producers (they can dump resin plastic granules), sectoral consumers (land -agriculture, construction, transport and leisure- or marine -fishing, aquaculture, transport and industry of high seas-), individual consumers (they dump plastics from food packaging, cosmetics or textiles) and, finally, waste management (GESAMP, 2015).

9.3.3.2. Plastic waste sinks

Depending on the composition of plastics, density and shape, they can be buoyant, neutrally buoyant or sink, distributing horizontally and vertically in the water column and in the seafloor (Cole et al., 2011). For example, polyethylene, propylene and many polystyrene foams are less dense than sea water and float, while vinyl chloride and polyethylene terephthalate sink (Andrady, 2015). The distribution also depends on other factors like winds, currents, coastline geography and human factors (urban areas, tourism and trade routes) (Li et al., 2016). In addition, due to their low degradation rates (it is estimated a range from 450 years to never), many of them remain in the ocean for decades (Parker, 2018).

In the marine environment, plastic slowly degrades into microplastics, and both macro and microplastics have been reported in multiple environmental compartments: surface waters, in the water column, sediments, sea ice and snow, the atmosphere and biota (killing each year thousands of fish, sea birds, sea turtles, and other marine species by ingesting or becoming entangled with plastic debris) (Kanhai et al, 2022; Dagupta, 2022). Data of plastics in the different compartments are not very accurate and they vary in the different consulted scientific sources. Figure 9.4 shows a diagram of plastic accumulation in ocean.

Considering marine litter in general, not just plastics, 15% is floating, 15% is in the water column and the remaining 70% is on seafloor (García-Rivera et al., 2017). Most of the plastic waste in marine environment is deposited on the seafloor (94%) and only a small percentage is on the ocean surface (1%) (Sherrington, 2016). Although some authors say that plastics on the ocean surface are 0.5 % (UNEP and GRID-Arendal, 2016).

The amount of floating plastic, according to some sources is around 0.27 million tonnes (Sherrington, 2016), and the subtropical gyres are hotspots for plastics. The North Pacific Subtropical Gyre is one of the major hotspots of floating plastic on earth. There are also big accumulations in the South Pacific, North Atlantic and Indian Ocean (Parker., 2018).

On the seafloor are about 25.3 million tonnes of plastics being the largest amount of marine plastics. The most visible and easiest to sample plastics on the coastline are those found on beaches having an average of 1.4 million of tonnes of plastics (Sherrington, 2016).

Many of the macroplastics break down and accumulate in the form of secondary microplastics, adding to primary microplastics. These accumulate in the same places that macroplastics, in addition to atmosphere-ocean interface (GESAMP, 2015). The maximum concentration was found in the North Pacific Gyre, with 10 particles of microplastics per square metre (Sherrington, 2016). There are many recent studies that show the problem of surface plastics in closed seas such as the Mediterranean Sea. This is the most affected area in Europe, and it has the fourth highest concentration of floating litter in the world (García-Rivera et al., 2017).

Microplastics have been reported in marine sediments worldwide leading to the belief that the depths of the ocean will become a long-term sink for microplastics. Estimated accumulation of microplastics in sediments is important to identify probable areas of accumulation (GESAMP, 2015).

Plastic debris can accumulate in marine biota, especially by direct ingestion, but also by entanglement in packaging bands, synthetic ropes and lines, or drift nets (Parker, 2018). Therefore, biota also may represent an important sink for microplastics (Derraik, 2002). Ingestion of plastics (the majority microplastics) can affect to multiple species worldwide, being seabirds one of the most affected. Other important case is green turtles, which increased their plastic ingestion a 20% in the period from 1985 to 2012, or the cetaceans increasing 11 times in number of affected since 1660 until 2010. This does not cause immediate death, although it generates adverse effects, leading to death (Li et al., 2016). Another form of

accumulation of plastics in biota reported since 1800s is by plastic entanglement. Li et al (2016), affirm in their study that entanglement is more frequent than ingestion.

“Missing plastics” are small quantities of microplastics that accumulate on Arctic Sea Ice and the deep-sea sediments (Sherrington, 2016). Plastics leak from the ocean represents a 1.4-2.8% (UNEP and GRID-Arendal, 2016).

9.3.3.3. Plastic transformations in the ocean

Although the interactions between plastic and microorganisms are poorly studied, it is known that oceans are not ideal disposal environments like composting or anaerobic digestion. Different plastic polymers, once they reach to the marine environment can undergo several transformations, resulting in the formation of secondary microplastic (GESAMP, 2015; Urbanek et al., 2018).

Degradation is the result of chemical changes in the structure of a polymer reducing its molecular weight. This is caused due to exposure to sunlight (photooxidation), but also by hydrolysis and biodegradation (Bond et al., 2018).

However, plastics can suffer fragmentation under abiotic factors (UV radiation, temperature, physical stress) for a long time, without decomposing or biodegrading (Urbanek et al., 2018). The 55% of plastic waste on the coast corresponds to three polymers: high-density polyethylene, polypropylene and extruded polystyrene. According to Bond et al (2018), these three polymers form microplastics after eight weeks.

Microplastics formation in oceans is influenced by many factors and depends on the polymer properties. Although there is not much information about the fragmentation of plastics in oceans, this is faster on the beaches followed by floating plastics, plastics in the water column and finally on the seabed. (GESAMP, 2015).

Marine biodegradability can be an important attribute for reducing the impact of plastic litter in the marine environment but varies between the different polymers (Al-Salem, 2019). Although biodegradation rate of plastic debris in the oceans is insignificant and it depends on the properties of the polymer, the biodegradable plastics will be more readily degraded (Li et al., 2016). Biodegradable polymers are degraded into small molecules such as CO₂, CH₄, and H₂O by the action of biota, but not all polymers with “bio” prefix are necessarily biodegradable (GESAMP, 2015).

Polymers like poly-ε-caprolactone (PCL), polylactic (PLA), polybutylene succinate (PBS), poly-(butylene succinate-co adipate) (PBSA) or poly-(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) are considered biodegradable plastics. Otherwise, polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS) or polyvinyl chloride (PVC) are considered non-biodegradable because they can take decades to centuries to degrade (Urbanek et al., 2018). The best biodegradable polymer is polyhydroxyalkanoate followed by starch materials. Starch, suffer a degradation of 9% in 49 days (checking in shopping plastic bags), completing degradation during long periods. Other polymers like polylactic acid are practically non-biodegradable. Still, the degradation time of polylactic acid is between 13-25 weeks, and degradation time of another polymer can be longer than 25 weeks (Müller et al., 2012).

Finally, other important data is that plastics can be a source of toxic chemicals in the environment. Many plastics have additives that end up in the environment, but this topic is not studied at all (Urbanek et al., 2018).

9.4. MODELLING OF THE PLASTICS FATE IN OCEAN

9.4.1. Review

In the plastic marine litter review, two hundred and sixty-seven papers were found over monitoring and modelling and more than half are published in the last two years. Only in the Most of them deal with macroplastics (ninety-four papers), although there are some that focus on microplastics (forty-one papers). Also, thirty-eight of them are combined with the marine diversity category, twenty-one with social political issues and twenty with management at the same time. Most articles deal with the spatial distribution of plastics in ocean (one hundred and thirty-seven papers) and they model their global distribution or the distribution in different oceans or located areas. The rest deal with input of plastic waste to marine environment (many from rivers), floating litter, monitoring, accumulation in different compartments of the ocean or accumulation in the ecosystems, and in marine biota.

Studies that analyse and model plastics in the sea are very frequent. In 2015, Maes & Blanke, show that the traceability of garbage can contain information about ocean circulation. Bai et al (2018) have created a model to forecast annual entry of plastics to ocean in China. For this, they perform an analysis of the material flow through the evaluation of the life cycle of plastic. Bruge et al (2018) present in 2018 the results monitoring the garbage in 3 years in the Adour River basin (south-western France). On the other hand, Bauer-Civiello et al (2019), estimate the plastics input in a river system through storm drains in a Tropical urban area. Van Emmerik et al (2019a) analyses the variation of plastic transport through the Seine River according to the flow. In the same river, Tramoy et al (2019), using the Jambeck statistical method, quantify the plastic flow with more precision. In 2019, the flow of river plastics originating in Jakarta was also estimated, using a combination of field measurements, empirical relationships, and hydraulic models (van Emmerik et al., 2019b). Cordier & Uehara (2019), focused on system dynamics, simulate scenarios designed to control plastic waste in the ocean. Turrel (2020) have performed simple models to predict the annual contributions of macro and microplastics to the Scottish coast.

Monitoring and modelling of marine debris worldwide are also a recurring topic, especially related to floating debris. In 2009, a review of plastics monitoring in the sea has been made to measure the changes in those wastes (Ryan et al., 2009). Van Sebille et al, in 2015, among other issues, aim to report the abundance and distribution of plastic debris in the ocean. Then, a study tried to identify the composition of the plastic materials found both on the coast and in sea turtles, through FTIR (Fourier Transform Infrared) spectroscopy (Mecozzi et al., 2016). In 2017, Hardesty et al, published an overview of the numerical simulation models that exist (based on ocean models), focusing on floating microplastics. These are key tools to obtain information about plastic distribution in the ocean. Working on the numerical modelling of plastic debris distribution, Liubartseva et al (2018) establish a bi-dimensional Lagrangian framework to track transport and fate of plastics in the Mediterranean. Studies based on deep learning can be found to identify floating plastic marine debris (Kylili et al., 2019). These debris can be detected by geoinformation obtained from Unmanned Aerial Systems. Topouzelis et al (2019), explore their viability. The marine research infrastructures are analysed by Ó Conchubhair et al (2019) with the aim of monitoring microplastics in the water column and quantifying their impact.

There are some studies about remote sensing of plastic litter using light reflectance of plastics floating (Goddijn-Murphy & Dufaur, 2018), monitoring floating macroplastics globally (Goddijn-Murphy et al., 2018) and studying Thermal Infrared Remote Sensing (Goddijn-Murphy & Williamson, 2019).

Many of the papers focus on the Mediterranean Sea and their internal seas, as well as floating litter too. In 2017, a floating marine litter transport model was built/developed using historical Lagrangian data from the Mediterranean Sea (Zambianchi et al., 2017). Crosti et al (2018), have done a monitoring of floating garbage with a fixed observation point located in rivers near the sea. A global plastic transport model is also carried out in the Mediterranean Sea (Liubartseva et al., 2019). Francheschini et al. (2019) use artificial neural networks to model the effect of environmental descriptors on the distribution of litter, estimating the amount of marine litter in the Central Mediterranean Sea (Francheschini et al., 2019). Moreover, Castro-Jiménez et al (2019), estimate the floating macro-garbage in surface waters of the Rhone River.

Other locations used as case studies were for example The North Pacific Gyre and Kuroshio current, Wang et al (2010) performed a follow-up model. A monitoring study was developed on the Baltic seabed (Zablotski & Kraak, 2019). The PELETS-2D Lagrangian Model is used in the North Sea for a transport simulation (Neumann et al., 2014). In the same sea, a distribution and accumulation of plastic model was found (Stuparu et al., 2015). The floating marine litter transport and stranding were studied in the French Riviera (Ourmieres et al., 2018) and in the Iberian Northwest. In the last place, the work tracks particles to analyse the effects of winds on the floating marine litter transport (Pereiro et al., 2018). A Lagrangian particle tracking tool is also used with high-resolution ocean circulation models in the Easter Island ecoregion (Gennip et al., 2019). With these high-resolution models, the quarterly variability of floating plastic was analysed in a protected area of Menorca (Spain) (Ruiz-Orejón et al., 2019). In the Black Sea, Lagrangian simulations are used to study floating marine litter concentrations (Stanev & Ricker, 2019). The transport and accumulation modelling of floating microplastics has also been studied in South Africa (Collins & Hermes, 2019). Finally, in Bahía de Banderas (Mexico) the seasonal variation in the abundance of floating plastic was monitored (Pelamattia et al., 2019).

The distribution and accumulation of plastic on the beaches is an issue that groups several found works. The first work of this group monitored plastic on beaches classifying waste into categories (de Araújo et al., 2006). In 2009, another work on plastic accumulation and its exposure to UV radiation and physical processes was published (Corcoran et al., 2009). Katakoa et al. (2013) analyse a beach as a linear garbage entry/exit system. In the marginal seas of East Asia, a prediction of the amount of plastic on beaches is made every ten years (Kako et al., 2014). Plastic detection programs have also been performed on beaches (Lavers et al., 2016). Fannini & Bozzeda (2018) addressed the dynamics of resin pellet deposition on a Mediterranean beach. In addition, there are papers that use linear models to create an application that predicts marine litter on beaches (Hérmendez-González et al., 2019). Finally, the creation of a marine debris map using an Unmanned Aerial System has been published (Gonçalves et al., 2020).

A little group modelled the accumulation of plastic in the marine ecosystems and biota. To start, the plastic impact on megafauna of Saronikos Gulf, in Aegean Sea (Katsanevakis et al., 2007). A monitoring plastic ingestion by *Fulmarus glacialis* was done in the North Sea (van Franeker et al., 2011). There are two models in Pelagos Sanctuary in Mediterranean Sea to predict the plastic accumulation in fin whales (Fossi et al., 2017; Guerrini et al., 2019). Finally, a paper that used linear model to predict the abundance of microplastics in Indonesian Manta Ray and Whale Shark feeding grounds (Germanov et al., 2019).

Finally, there are some papers that do not refer to any of the themes mentioned above. For example, Material Flow Analysis to Household Solid Waste and Marine Litter on a Small Island Developing State (Republic of Palau) was found (Owens et al., 2011). Holmes et al (2014) study the role of estuaries in modifying the adsorptive properties of new and aged plastics towards trace metals. In the same way, in an estuarine gradient, marine debris' transboundary

was studied through hydrodynamic models, ground truthing estimates and regressive vector analysis (Krelling et al., 2017). In 2019, Martins et al (2019) made predictions of quantity, distribution and plastic pollution effects on marine ecosystems in order to develop in a future a numerical model. Although numeric models and analysis, also help to definition of marine litter clean-up and mitigation strategies at an estuarine scale (Núñez et al., 2019).

9.4.2. Modelling

Due to the dynamic nature of our system, system dynamics is used for studying and managing such as complex system which change over time, as a method of analysing problems in which time is an important factor (Fishwick, 2007; Ford, 1999). The dynamic problem studied with the model is the accumulation of plastics in the marine environment: once plastics enters to the ocean, they distribute in different media, multimedia dynamic modelling is developed implementing four model's phases increasing gradually the complexity.

A model is a simplified representation of reality that emphasizes those aspects that are considered important and omits all those properties considered non-essential (Silva Gómez et al., 2005). According to Silva Gómez et al (2015) models can be classify considering different parameters such as time, space, descriptive level or mathematical formulation. Accordingly, models developed in this chapter are dynamic (the interesting thing is to know the evolution of plastic over time), theoretical (there is knowledge of the physical principles of the system, providing the model with great versatility), deterministic (they are not executed with random variables, involving a complexity of calculation, providing acceptable long-term results), multimedia (representing the movement of plastic between various phases).

The developed model represents the accumulation of plastics in different ocean compartments: surface, water column, seafloor and mobilization of microplastics to biota. Once the model is calibrated and validated, Dynamic Material Flow Analysis (MFA) can be executed running it. MFA is a tool that comes up with focus of system dynamics, and these models provide a method for connecting the material flows into and out of a defined system (Owens et al., 2011). Sensibility analysis is applied to identify the parameters running the system and scenarios are design to be studied using the model.

The selected software is Vensim PLE, available to build flows and stocks diagrams and modelling based on it (Ventana Systems, 2020).

9.4.2.1. The Model

The model consists of four phases. Each phase will incorporate more elements in order to complicate the model. The phases of the model are:

- First phase of the model: it only takes into account the input of both macro and microplastics into the ocean and the degradation from macro to micro. In this phase, the amount of both macro and microplastics in the ocean is obtained.
- Second phase of the model: it incorporates data on the amount of macro and microplastics floating. Therefore, from the second model, the amount of both macro and microplastics that float and both macro and microplastics that sink are obtained (it is assumed that everything that does not float will sink).
- Third phase of the model: it incorporates data from both macro and microplastics that sink and float, assuming everything else stays in the water column. This phase, therefore incorporates one more compartment for both macro and microplastics. Obtaining plastics on the surface, in the water column and on the seabed.
- Fourth phase of the model: it incorporates the ingestion of microplastics by the biomass of fish in the sea. Therefore, this last model incorporates one more compartment to the

surface, water column and seabed, which would be the biomass of fish, obtaining amounts of microplastics ingested.

9.4.2.1.1. *Model's phase first*

This is the simplest phase of the model, that shows the total worldwide accumulation of plastics (macroplastics and microplastics) in oceans, being both the two existences (accumulation variables) of the model. Three flows are considered: “input of primary macroplastics to the ocean”, “input of primary microplastics to the ocean” and “macroplastics fragmentation to microplastics in the ocean”. Figure 9.5(a) shows the flows and stocks diagram of the first phase developed in Vensim.

This model is based on the annual plastic production. Therefore, historic data on the amount of plastic produced in different years from 1950 to 2020 have been compiled.

Parameter estimation: to calculate the input of plastics into the ocean, a rate of 3% is applied to annual production. Although this data is estimated for 2010, it is believed that it can be similar for other years (Ritchie & Roser, 2018). According to Sherrington (2016), 12.2 million tonnes of plastic end up in the ocean, of which 0.95 million tonnes are microplastics. From this data the percentage of macroplastics and microplastics can be extrapolate. The 92% as macroplastics and the 8% as microplastics.

The macroplastics fragmentation flow to secondary microplastics into the ocean is calculated considering data from polyethylene compounds, one of the most abundant plastic types in the marine environment (54.6%), followed by propylene (16.5%) and polystyrene (9.7%) (La Vanguardia, 2019). Therefore, all plastics present in the ocean are considered as polyethylene in terms of fragmentation. Macroplastic size is assumed as 500µm (standard size of a water bottle). Fragmentation data for different polymers in the marine environment exist for polyethylene compounds: PET (110 µm / year), HDPE (9.5 µm / year) and LDPE (10 µm / year) (Chamas et al., 2020). Therefore, an average of 43 µm/year is assumed. Knowing that a macroplastic of 500µm and a fragmentation rate of 43µm/year have been assumed, it will take 12 years to fragment a macroplastic to microplastic.

The model has been runned from 1930 to 2020 (last year with data) with a time step of one year. Initial values for existences in 1930 introduced to the model are zero million of tons of both macroplastics and microplastics in the ocean. The model runs with a time step of one year considered the fragmentation rate, reason for what introduced historical data are annual.

Figure 9.5 (b), (c), (d) show the results of simulation, Figure 9.5 (b) represents the direct input of total plastics to the ocean (green), the primary microplastics input (red) and the macroplastics input (blue). The total plastics input in the system increases over the time. In 1993 there was a total input of 4.41 million of plastic tonnes and in 2020 this quantity increases until almost 11 million of tonnes. In the same way, primary microplastics and macroplastics increase. The trend of these last are the same that total plastics. The input of primary microplastics to the ocean is lower than macroplastics, representing a very low percentage of the total. Figure 9.5 (c) shows that the flow of macroplastics that fragment into microplastics increases over the years, although the first years are minimal or null. Figure 9.5 (d) shows that the macroplastics accumulated in the ocean are higher than microplastics until 1990, but in 1991 this trend changes. In 2020 the result obtained is 176.9 million tonnes of microplastics and 117.3 million tonnes of macroplastics. This model evidences that the plastics size varies greatly in the marine environment.

Although the amount of plastic in the ocean is unknown, there are estimations that the amount of microplastics is higher than macroplastics. Yuan et al (2020) estimate that

microplastics account 92% of plastic waste in the ocean. Although this value is not observed in the model, this follows the same trend in recent years being higher the amount of microplastics.

There are sources (European Parliament, 2018), which state that 69-81% of microplastics in the ocean correspond to secondary microplastics. This model shows a very low primary microplastics input to the ocean regarding to the accumulated quantity. This is explained by the fact that most of the microplastics are secondary due to fragmentation.

One of the most common and significant tests for model validation is to set the inputs to the model at their historical values and see if the outputs match history. The first phase of the model is in line with estimates found in the literature. Richtie & Roser (2018) affirm that in 2010, 8 million tonnes of plastic ended up in the Ocean. In addition, Jambeck (2015) estimates that between 4.8 and 12.7 million tonnes of plastic would end up in the sea. This model almost exactly matches data of 2010. Figure 9.5 (e) shows the approximation to 8 million tons in 2010.

In addition, Yick et al (2022) state that 243.978 million tonnes of plastic in the ocean have been estimated, and the sum of both the accumulation of macro and microplastics shown by our model is very close to that value. The value of the model is 294.2.

The sensitive parameters of the first phase of the model are: the plastics rate to the sea from production; both micro and macroplastics rates; and macroplastics fragmentation half-life to microplastics in the ocean.

- Plastics rate input to the ocean: if this parameter is varied, the other parameters that depend on it will change. For example, if it increases, the micro and macroplastics also increase.
- Macro and Microplastics rate: if macroplastics rate increases, the microplastics rate would decrease, reducing the primary microplastics. The macroplastics rate is very sensitive and increasing it would make an unrealistic model.
- Macroplastics half-life to Microplastics: if the macroplastics half-life before fragmentation increases, the microplastics would not increase as much. Otherwise, if it is reduced, microplastics would increase much faster.

The accumulation of plastics in oceans increases with time because the new plastic input adds to the plastic already accumulated in previous years, and this happens because plastic biodegradation rate is minimal and may take decades to occur.

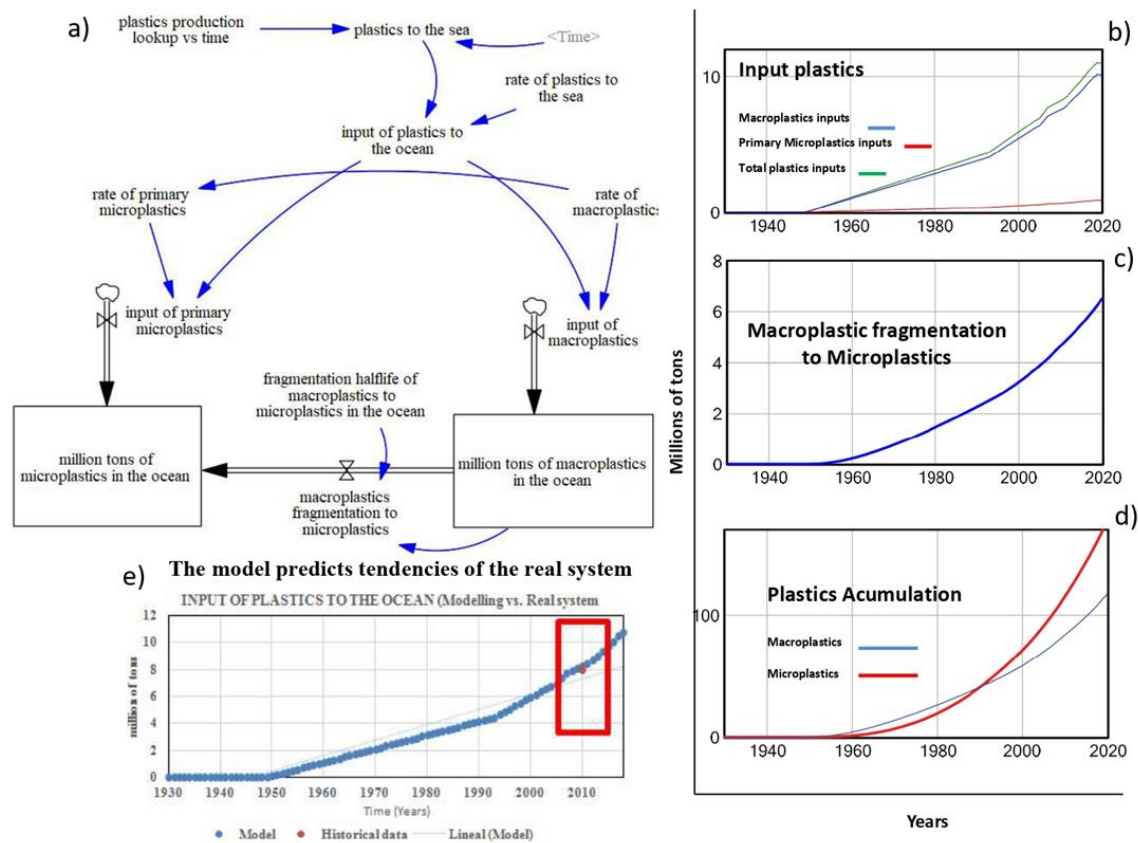


Figure 9.5. First simple system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim

9.4.2.1.2. *Model's phase second*

The second phase of the model aims to visualize in which part of the ocean the plastics will accumulate. Showing how many micro and macroplastics are in both the water column and the ocean surface, being these the four existences of the model. Six flows are considered: “input of primary microplastics”, “input of macroplastics”, “macroplastics from surface to water column”, “microplastics from water column to surface”, “macroplastics fragmentation to microplastics (ocean water column)” and “macroplastics fragmentation to microplastics (ocean surface)” (Figure 9.6 (a)).

Parameter estimation: to run this phase, the input data of the first phase of the model are used, knowing that only 1% of the macroplastics are superficial (Sherrington, 2016), and 0.5% of the microplastics that input to the water column, float (UNEP and GRID-Arendal, 2016).

Unlike the first phase, it is necessary to consider that the half-life before fragmentation can be different for plastics in the water column or plastics on the surface. Plastics on the surface or floating are affected by solar heat conditions and ultraviolet radiation, whereas those of the water column not so much. To calculate the half-life of the floating plastics before fragmentation, the data defined in the first phase of the model for marine conditions were used by averaging the three PET polymers (PET, HDPE and LDPE). For plastics in the water column, the same was done but, in other conditions of heat and radiation. The same value for both was obtained, 12 years (Chamas et al., 2020).

Primary microplastics reach to the water column is assumed. Their main sources are terrestrial and by wastewater systems that have an output to the water column, as emissaries. To calculate the flow of microplastics from the water column to the surface, the amount of microplastics is multiplied by 0.005 (as described above, the 0.5% floats). Macroplastics instead, input to the ocean surface directly. To calculate how many of these macroplastics stop floating, the input quantity is multiplied by 0.99 (the 1% are superficial). Finally, two fragmentation flows from macroplastics to microplastics are calculated (the half-life before fragmentation is the same in both column water and surface, 12 years).

Like the first phase of the model, the second runs from 1930-2020. Figure 9.6 (b), (c), (d) show the results of simulation, where Figure 9.6 (b) shows that the most of plastics are in the water column (red), compared to the few floating plastics (blue). In 2020 there are less than 10 million tonnes of floating macroplastics, compared to 27.7 million tonnes of floating microplastics.

Figure 9.6 (c) shows that the amount of microplastics is higher, as the first phase of the model. In both micro and macroplastics, the difference between floating and non-floating is very noticeable. Figure 9.6 (d) shows how the formation of secondary microplastics increases over time due to the fragmentation.

The results obtained in this phase are expected. Most of the scientific literature claims that the greatest amount of plastic is not found on the surface. Although it is the most studied plastic type, there are very different estimates.

This phase, like the first, is very sensitive: to the half-life before fragmentation, to the rate of plastics and the rate of macroplastics. If a larger size were assumed for macroplastics, there would be fewer microplastics. Also, if a different plastic than PE were assumed, with a different fragmentation rate, the model would vary significantly.

This phase of the model obtains a large amount of floating plastic, compared to bibliographic estimates. This is due to the rate of movement towards the water column or towards the surface since there is not enough data available.

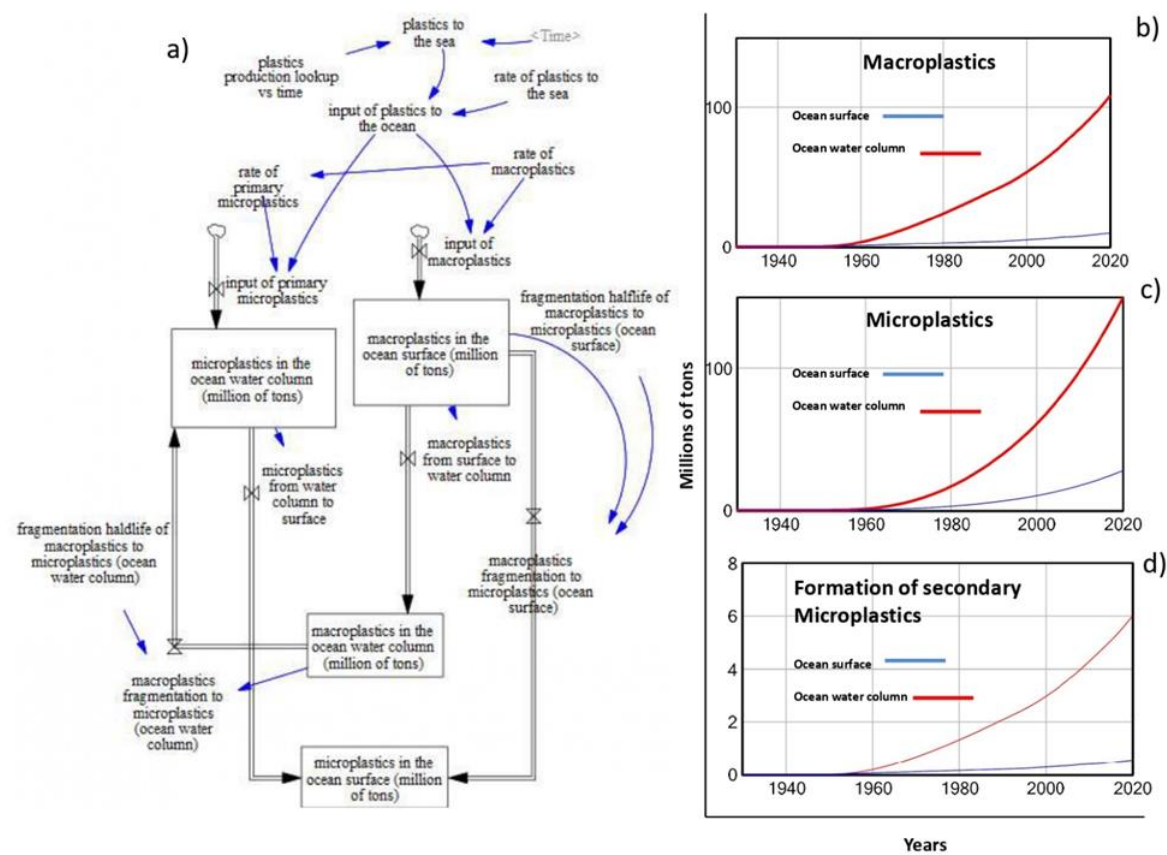


Figure 9.6. Second system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim

9.4.2.1.3. *Model's phase third*

The dynamic problem is amplified for the third phase, where the main objective is to know the amount of plastic that accumulates in the sediments. The accumulation of both, macroplastics and microplastics on three stocks each one (six existences): on the surface (floating plastics), plastics that remain in the water column and plastics that fall to the ocean floor as shown in Figure 9.7(a). Moreover, nine flows are considered: “input of primary microplastics”, “microplastics from water column to surface”, “microplastics from water column to seafloor”, “input of macroplastics”, “macroplastics fragmentation to microplastics (ocean water column)”, “macroplastics from surface to water column”, “macroplastics fragmentation to microplastics (ocean surface)”, “macroplastics from surface to the seafloor” and “macroplastics fragmentation to microplastics (seafloor)”.

The input data for this phase is the same as for the first and second phases, based on annual plastic production. It is also run for the same period, 1930-2020.

This phase of the model assumes that macroplastics reach the ocean directly to the surface, one part goes towards the water column, and in this case another part will go to the ocean floor. For microplastics, it is assumed that them reach the water column, and one part will move to the surface and another to the bottom.

Figure 9.7 (a) shows the third flows and stocks phase. From the stocks of macroplastics, different fragmentation flows are defined towards the stocks of microplastics. In this case, there are three fragmentation flows from macro to microplastics, one on the surface, one in the water column and the last one on the seabed.

Parameter estimation: for these three flows, the same half-life before fragmentation was used as in previous cases (12 years) and the same size of macroplastics as in the two previous cases (500µm).

In this phase of the model, it is necessary to know that 94% of the plastics that enter the ocean each year will go to the ocean floor (Sherrington, 2016). Therefore, as we already knew that 0.5% of microplastics remain on the surface (UNEP and GRID-Arendal, 2016), we can calculate that 5.5% remain in the water column. The amount of macroplastics that remain on the surface is also known, being 1% (Sherrington, 2016). Therefore, 5% macroplastics will remain in the water column.

Figure 9.7 (b), (c), (d) show the results of simulation. Figure 9.7 (b) shows the amount of macroplastics in each compartment. The green line, which represents the macroplastics on the ocean floor increases considerably over the years. The same occurs in the Figure 9.7 (c), which represents the amount of microplastics in each compartment.

Figure 9.7 (c) represents the fragmentation of macroplastics to microplastics. The majority of the macroplastics pass to the seabed each year. Because the same fragmentation rate applies to all three parts of the ocean, it is normal for the largest contribution of secondary microplastics to be at the bottom.

This phase, like the previous one, is very sensitive to the parameters of half-life before fragmentation, the rate of macroplastics (and microplastics) and the rate of plastics to the sea.

In addition, this phase shows how macroplastics and microplastics are distributed throughout the ocean water column once they reach the environment. Showing theoretical amounts of plastic that can accumulate over the years in marine sediments.

All current estimates say that most marine plastic is not found on the surface, although it is the part of the ocean more studied. Some studies say that plastics in sediments are 94% of the total (Sherrington, 2016). But there are others that estimate, for example, 70%, on the European coasts (Galgani et al., 2000). This agrees with the model results.

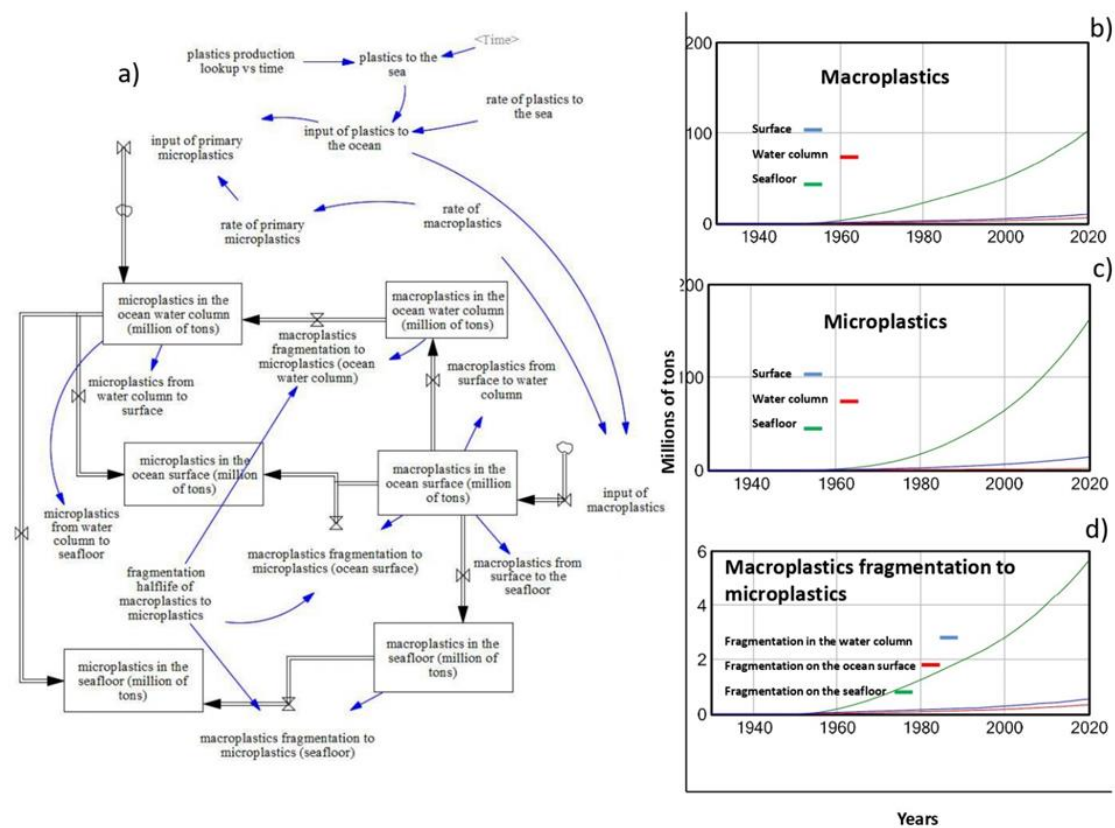


Figure 9.7. Third system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim

9.4.2.1.4. *Model's phase fourth*

Unlike the previous phases, the fourth phase focuses only on microplastics. Specifically, in the movement of microplastics from the ocean to the biota.

Therefore, the dynamic problem in this case is the accumulation of plastic in the three zones of the ocean (surface, water column and sea bottom), but focusing on microplastics that can potentially be mobilized to marine biota. Therefore, this phase has seven existences that are the same of the third phase adding “microplastics ingested by fishes” Figure 9.8 (a).

To create this phase, it is assumed that most of the microplastics that move to the biota are those that are in the water column. It is also assumed that all biota are fish.

Parameter estimation: data collected for this phase is the same as for the third phase. The new flow "microplastics in biota" is calculated based on the average amount of microplastics ingested by fish. Boerger et al (2010) estimate an average intake of 1.57 mg of plastic per fish, in addition, based on this chapter, the amount of microplastics per ton of fish in the sea can be estimated, obtaining a value of 0.6 kg of microplastics per ton of fish.

For this phase it is necessary to know the biomass of fish in the ocean, this data is observed in several works that can estimate it, obtaining an average of 1.5 mil millions of tonnes of fish in the sea (Tremblay-Boyer et al, 2011; Wilson et al 2009 Jennings et al; 2008).

The fourth phase model runs just like the previous ones between 1930-2020. Once run, simulation results in the microplastics stocks on the surface and sediments and for the macroplastics are as expected. The difference in this phase is centred on the microplastics in the water column (microplastics ingested by fish).

As microplastics increase in the ocean over time, their ingestion by fish also increases (Figure 9.8 (b,c)). Microplastics show an upward trend over time into the future. The amount of microplastics in biota in a real-world scenario is thought to be lower, due to removal through fishing or other activities. Still, fish can capture a worrying amount of microplastics through ingestion. Figure 9.8 (b,c) shows the tendency of microplastics to increase, despite the flow to marine biota.

Like previous phases, this one is sensitive to the half-life before fragmentation, the rate of macroplastics and microplastics and the rate of plastics in the sea. In addition to these sensitive points, the quantity of fish in the ocean is added. If this amount increases, the amount of intake will be higher.

As a result, this phase shows that in 1952 there was already a movement of microplastics to fish. Instead, the quantity began to increase and, in 2020 there are more than 7000 tonnes of microplastics accumulated in fish. Although there are studies in local areas, like Carson (2013), which estimates that fish ingest 1.3 tonnes of microplastics per year in an area of 15 km², models for the amounts of microplastics ingested worldwide have not been found. Therefore, to compare the result of this model with historical results to date is very difficult.

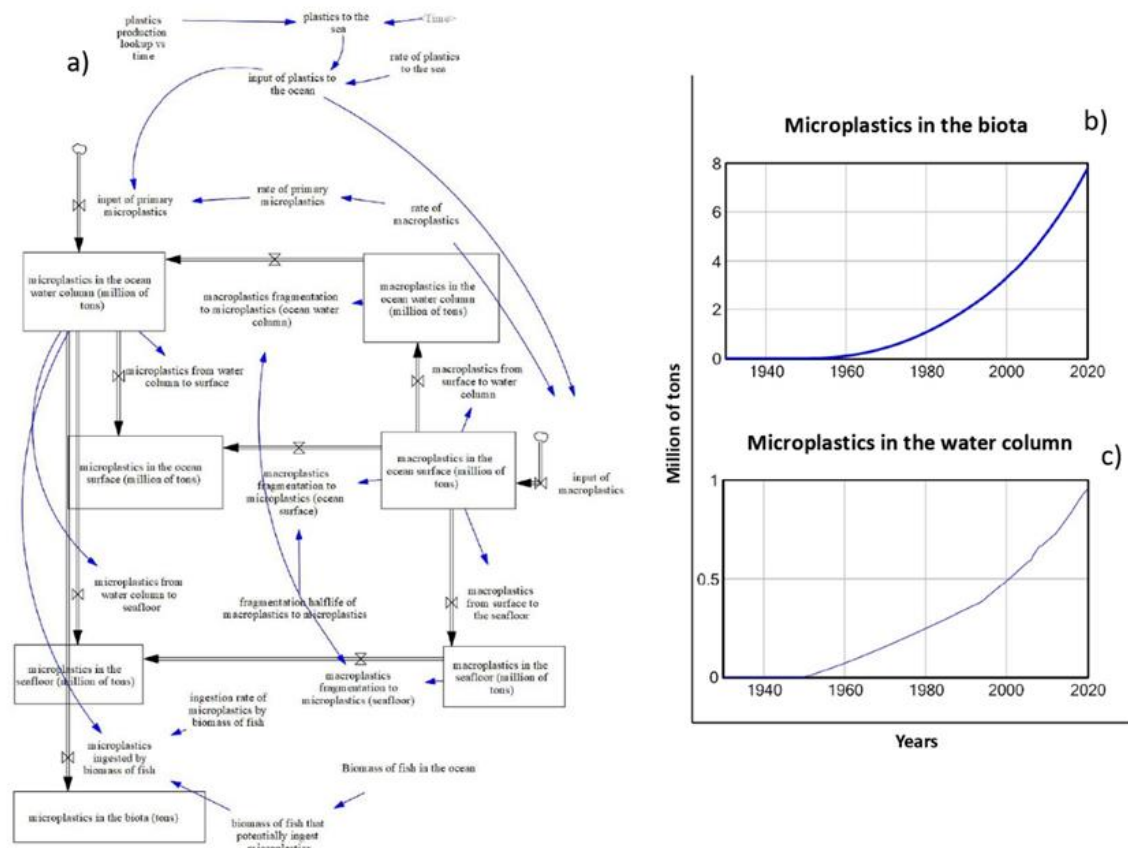


Figure 9.8. Fourth system dynamics model of mobilization of macroplastics and microplastics in the marine environment developed with Vensim

9.5. RESULTS AND DISCUSSION

Nine hundred and seventy-eight articles have been reviewed and analysed to study the origin, sources and sinks of plastic. Estimates of the amount of plastic in the sea are very different depending on the media consulted. According to the collected articles, the sources can be classified into terrestrial and oceanic sources. It is considered that 80% (Sherrington, 2016) of the inputs are from land sources compared to 20% of the oceanic inputs.

On the other hand, the plastics more abundant are the classified by Parker (2018) as Others (O), LDPE and PP. These plastics are not biodegradable and can accumulate in five compartments: surface, water column, seabed, littoral and in biota. Most of the studies reviewed correspond to floating plastics found on the ocean surface. Although the ocean surface is the most studied, the compartment with the highest concentration of plastic, with 94% is the seabed (Sherrington, 2016).

Regarding the transformation of plastic in the marine environment, it follows that the marine environment is not a means of disposal, although it undergoes transformations, it tends to accumulate.

After reviewing the nine hundred and seventy-eight papers, a classification grouped by themes is obtained (Figure 9.3). The more repeated topic was “macroplastics/mesoplastics”. Although the topic “Microplastic/nanoplastics” is less represented it is very current. From all studies that deal microplastics, 36% of these were made in two last years.

Management strategies are represented in 15% of the articles reviewed. These are related to plastic management strategies to reduce its impact or legislation. This is a very current topic, the 33% of studies were found in two last years. For this reason, there is no notification of many strategies to manipulate plastic in the oceans. The more important projects are Clean Atlantic (Interreg Atlantic Area, 2020) and Ocean Cleanup (The ocean clean up, 2021). On the other hand, citizen science campaigns such as the Spanish project “Libera, unidos contra la naturaleza” (Proyecto Libera, 2020).

It was found that two hundred and sixty-seven of papers reviewed represent the topic “monitoring and modelling”. This topic has an upward trend in terms of number of studies in recent years. In the two last the articles reviewed were the 51%. Nowadays there are models of the spatial distribution focused on local areas as Mediterranean Sea (Manusi et al, 2020).

After the reviewing, four model's stages have been built from the simplest to the most complex that represent the mobilizations of the plastic between the oceanic compartments.

Using plastic production data and fragmentation rates, from the simplest to the most complex model's stages were run. More data have been added to increase the complexity of the phases of the models. For the simplest phase only the accumulation of macroplastics and microplastics is considered. Then the oceanic compartments are gradually included for both macroplastics and microplastics. The compartments are floating plastics, plastics in the water column and plastics on the seabed. The last phase of the model, and the more complex uses data from the previous phases. In addition, a new compartment is included, the biota, only considering the accumulation of microplastics. Main results found by model's stages are:

- Model's stage 1: High input flow and great accumulations of microplastics and macroplastics.
- Model's stage 2: Floating plastics are the least abundant.
- Model's stage 3: Seafloor is a great plastic sink, especially microplastics.
- Model's stage 4: Great number of plastics are moved to the biota.

Studying data from the bibliography it is observed that this model is very close to a real system. Similarities have been observed in this model, such as the 8 million tons that ended up in the ocean in 2010 (Richtie & Roser, 2018). Most of the marine plastic accumulates in seabed, but

there are not currently many sources handling this data globally, although all scientific sources say that this percentage is very high in the local areas sampled (Sherrington, 2016). There are several works that show that there are more microplastics than macroplastics in sediments, or at least in the local areas where the samples were collected. For example, a study of plastic litter in sediments in the Telascia Bay Nature Park (Croatia) says that 88.71% of the plastics sampled are microplastics (Blaskovic et al., 2017). Another study in an archipelago in the Tyrrhenian Sea states that 94.3% of the plastic represents microplastics (Fastelli et al., 2016).

Regarding the model's stage fourth, it is observed that the transfer of microplastics to the biota is increasing. Microplastic particles have been found worldwide in marine animals (Covernton et al, 2021), this may be due to the increase of microplastics in the water column. Although this stage of model is not easy to compare with a real system, since currently the knowledge of the trophic transfer of microplastics is still scarce (Hasegawa and Nakaoka, 2021). This last stage of the model adapts previous data by adding new information, thus, it is the closest stage to the real system.

9.6. CONCLUSIONS

This document expands the current knowledge about plastic as a pollutant in the marine environment and offers a broad overview of plastic pollution in the sea. It reviews the problem of marine plastics and develops a dynamic MFA by preliminary models on the mobilization and accumulation of plastics in the marine environment.

First, a bibliographic search was carried out and it was classified into seven categories according to the most important topics found. From this review, a research work that analyses current management strategies is obtained. Most of the papers are about management measures on land to prevent the plastic's arrival in the marine environment. The citizen campaigns for the elimination of plastics and various national and international projects stand out among other strategies. Although these are fundamental to face the problem of plastics, few studies or strategies have been found. Improving the knowledge about the methodologies and techniques for studying micro/nanoplastics will help to define better strategies.

In addition, the review provides knowledge of the main sources and sinks of plastic into the ocean. Therefore, it is collected that the land source represents 80% of the plastic inputs to the sea and the seabed, which is a large sink (most of the plastic waste in the marine environment is settled to the bottom of the seafloor). Information is obtained on the transformations that plastics undergo in the sea (degradation and fragmentation) even though the marine environment is not a means of disposal, but of accumulation.

This chapter has demonstrated the usefulness of the model to study dynamic problems. The dynamic problem studied with the model is the accumulation of plastics in the marine environment: once plastics enters to the ocean, they distribute in different media. Four phases of a dynamic model that represent the mobilization of plastic in the ocean are developed, progressively increasing the complexity.

The model shows that plastic debris in the form of macroplastics, microplastics and secondary microplastics in the ocean continues to increase over the years, mostly in the water column. Most of it ends up being accumulated on the sea floor, but the plastic's increase in the water column causes at the same time the increase of plastic in living beings, also affecting humans.

The developed model describes well the real system trends in the different media. The model is sensitive to parameters that can be modified to consider other possible scenarios: plastics index entry into the ocean, macro and microplastics rate, the half-life of macroplastics to microplastics and the number of fish in the ocean. Adapting and adjusting the model can

predict future trends in plastics. Being modelling a useful tool to support new regulations and strategies to deal with the problem of plastic waste. This chapter has expanded knowledge about the real problem of marine plastic debris pollution around the world.

CHAPTER 10. CONCLUSIONS

The main objective of this thesis was to contribute to the identification of sustainable techniques to facilitate the path towards a regenerative economy. Through a life cycle approach, human activities related to the sea as a provider of food raw materials and as a host for enjoyment activities are analysed. This allow to achieve a cleaner ocean from which to obtain resources in an efficient and sustainable way, protecting it by reducing the environmental pressures associated with different human activities such as fish and seafood transformation, the fishing and enjoyment.

The objectives of this thesis were divided into three parts. The first part deals with fish and seafood transformation activities. The second part deals with activities related to the fishing sector. The third analyses those activities around the sea as a place of enjoyment. Material and energy analyses were carried out to identify impacts of resources and waste, and propose solutions based on the Best Available Techniques. Chapter 9 is dedicated to plastics in the sea that come from all the previous activities, the analysis of the flows was carried out dynamically, through the modelling of flows and stocks, and the development and application of a multimedia model that predicts trends behaviour of these compounds. Each part is composed by two chapters; therefore, this thesis is made up of 6 main chapters in addition to Introduction, Objectives, Methodology and Conclusions. In these 6 chapters, the work was contextualized and justified, as well as concepts related to the tools used throughout the thesis were introduced. In each of these 6 chapters, an introduction was made to the technologies analysed and their contribution to the circular and regenerative economy was analysed and discussed.

The first part that deals with fish and seafood transformation activities. CHAPTER 4 applied a methodology that combines tools based on life cycle thinking. It combined several tools to analyse a plant of transformation of octopus and proposed techniques that can improve the process from a sustainability point of view. It is a simple system that combined MEFA, applying the calculation of the carbon footprint to identify the IFs. Finally, a BAT analysis was applied to identify candidate techniques to improve the most important flows. The objective of this combination of tools was to achieve a more sustainable configuration.

The results observed for this combination of tools was a plant with a not very high degree of BAT implementation, with twelve techniques already implemented and twenty-nine possible that could be implemented. It is expected that although the degree of implementation is not very high, that currently the degree of implementation has increased. These techniques not only help improve flows and contribute to a more sustainable process. They also contribute to a more profitable process by reducing the consumption of electrical resources, water and diesel used in the process. Therefore, the application of this methodology provides effective solutions to the octopus's transformation to make it more sustainable and profitable. Thus, achieving a sustainable configuration, helping the company on an economic, environmental and social level. The application of the technologies identified in the BREF as BAT therefore contributes to preventing and reducing environmental pollution. Therefore, the application of this methodology turned out to be a good tool to locate possible critical points that can be improved and obtain a sustainable process.

Fish and seafood transformation activities like the one analysed, is a powerful sector in Galicia. Specifically, canned mussels generate a large amount of waste that is difficult to manage. Mussel shells are a very important waste due to the amount generated in Galicia.

Although there are plants that use this waste as a recovery process, odour emissions into the atmosphere become a problem. Due to, CHAPTER 5 identified the sources of pollution caused by this plant and sought solutions and options for odorous emissions. The case study of this chapter was a pioneering activity in the thermal recovery of mussel shells by reusing waste as resources. This means that each unexpected technical failure was faced without prior history. Therefore, the organization was a source of new experiences in technological development. Obtaining the environmental permit required to operate as established in the IPPC was an impetus to audit and monitor odour emissions, reduce their generation to the environment through the aforementioned measures and best environmental practices, and improve the operating conditions of the equipment and the facilities. However, despite the efforts made over the years to improve the production process, hard work will still be done to prevent and/or control the environmental impacts derived from the valorisation of the shell. Despite the variety of prevention and mitigation alternatives proposed, odour problems are best addressed at their source, by designing or modifying the process, or even managing the activity differently (UKEPA, 2002). Therefore, the best odour management program for the process analysed, the valorisation of the mussel shell, should include a complete redesign of the process, taking into account the conclusions drawn from this chapter, which has indicated that the most odorous treatments are thermal treatments, followed by storage of raw materials. Operating procedures must also be updated to eliminate practices that may affect the total odour emissions released by the plant.

To conclude the first part, these two chapters showed how to mitigate the impacts produced by fish and seafood transformation activities. It focused on the processing of food resources that come from the sea and the impacts generated by the recovery of the waste produced by these companies. It is of great importance to reduce the impacts of this sector both in the production process of its products and in the recovery of its waste, since it is one of the main industrial activities in the community of Galicia.

On the path to obtaining clean oceans and contributing to the regenerative economy, the most relevant activity is fishing and its waste. Because of this, the second part deals with activities related to the fishing sector. A tuna purse seine was analysed and the most important waste generated in this fishery was investigated, which is FAD. CHAPTER 6 defined more sustainable configurations of a tuna purse seine. To this end, a methodology was proposed applied previously but to date never applied and validated in a mobile system, the Draco purse seiner. The criteria considered for the analysis were framed in the Integrated Pollution Prevention and Control approach, developed in the EU for potentially industrial polluting sources, as well as in the approaches of both industrial ecology and Life Cycle Thinking. In this context, the tools used combined for the analysis of the system were: “Analysis of material and energy flow” (a tool derived from industrial metabolism, which analyses improvable flows) and “Analysis of the best available techniques” (a tool derived from (integrated pollution prevention and control approach). “Materials and Energy Flow Analysis” provides a way to detect “Improvable Flows” in a system, and “Best Available Techniques Analysis” provides a way to define sustainable options to improve these “Improvable Flows”. The application of the BAT identified to the IF allows defining a more sustainable configuration of the tuna seiner.

The study of this system was difficult to simplify into a single model due to the nonlinear consecutive processes. Several assumptions were made to model the system according to the literature. There was a significant amount of information on BAT in the food industry, but there was an evident lack of studies of this industry in mobile systems. The main environmental problems of this type of ships are high fuel consumption and emissions into the atmosphere, especially NO_x. This was due to the large dimensions of the boats, the powerful engines

necessary for the long distances they must travel between the fishery and the port, and the freezing power necessary to keep the product at an adequate temperature. From this chapter we could also deduce that large fisheries, in which boats have to travel long distances and remain in fishing grounds for months, would also have a similar IF. In this way, the results presented in this study can be easily compared with those of vessels enrolled in fisheries that travel long distances. The practical application of the identified technologies to fishing systems will contribute to preventing and reducing marine pollution, a major threat to the oceans. Finally, this methodology proved to be a good tool not only towards sustainable punctual systems, but also towards sustainable mobile systems such as fishing activity in oceans, as validated here by the tuna seine.

The most relevant waste from these fisheries are fish aggregation devices or FADs. Due to the large number of FAD that remain at sea, CHAPTER 7 presented a systematic review of the state of the art. All available bibliographic information was compiled and the most relevant study topics on FADs were presented. Once the most relevant information on these devices has been collected, the biodegradable materials that best adapt to the characteristics of the FAD were compiled. With this compilation, biodegradable solutions were obtained with which to manufacture FADs that are often abandoned in the sea. Therefore, it was concluded that these (FADs) are of great importance for fishing due to the aggregation behaviour of fish. Currently it is estimated that around 100,000 FADs are released per year (Murúa et al, 2023). Due to the high density of FADs in the ocean, their manufacturing materials and the fact that many are lost and abandoned, they can generate many environmental impacts. Among other impacts, stand out marine pollution, although the change in the behaviour of many marine species could also be important.

On the one hand, good common and international management of these devices would be a way to reduce not only the amount of FADs in the sea, but also the waste generated by FADs. In this way, the impacts generated by the plantations on the different species and the waste generated would be reduced. On the other hand, research into biodegradable materials resistant to the environmental conditions of the sea is of great importance for the manufacture of these devices. As has been seen, residues from tropical fruit plantations such as pineapple are a suitable alternative to produce PHB and can be used as fishing nets and FADs. For this, it is necessary to carry out more exhaustive research to make it more suitable and profitable. This would be the second step to this investigation. These biodegradable materials can help reduce waste from the food industry and the large amount of waste made up largely of fishing nets and FADs. In this way, waste becomes a safe and natural resource, contributing to the circular economy.

The third part of the thesis analysed those activities around the sea as a place of enjoyment and the plastics waste that come from all the previous activities. Enjoyment in the sea and all related activities, such as the manufacturing of products and equipment used, as surfboards generate a great impact in the environment.

CHAPTER 8 analysed the manufacturing of a small surfboard production plant and presented a methodology intended to use sustainable indicators in a production process. The methodology combined three tools: the MEFA, the BAT analysis, and the Impact Analysis. The methodology has been validated in a small surf-boards production job-shop. Ten Improvable Flows have been identified for the process; consequently, fifteen candidates BAT have been proposed aiming to act upon these flows. The combination of MEFA and BAT analysis has confirmed to be a very good option for process evaluation considering sustainability criteria. The use of USEtox model has permitted to compare the base case scenario with the improved one in the basis of toxicity impact. The Excel spreadsheet resulted of easy use although the

large quantity of data presented. The results achieved with the calculation of the IS relative to the two scenarios from the CFs of USEtox, demonstrated consistency with the expected results, and showed the reduction of the impacts after the application of the selected BATs. This methodology has turned out to be applicable also to a job-shop that apparently does not seem have impacts because of its restricted and simple industrial metabolism. On the one hand MEFA obtains deep information about the environmental aspects of the process can be extracted to identify the IF (whether they are inputs, outputs or internal flows). On the other hand, BAT analysis and its adoption, which helps in considering not only environmental aspects but also economical that may affect the selection of techniques, the environmental performance can be improved, and this job-shop may be transformed into a “low impact” plant. These results are very useful to enhance the process efficiency. Resources consumption, waste and emissions generation are reduced and, at lower level, economical aspects are considered to not affect them. Due to these reasons this chapter is endorsed to fall within the Circular Economy model. Finally, this chapter can be applied to a manufacturing of marine equipment that use the same material and amplifying the system to a large industry.

The CHAPTER 9 expanded the current knowledge about plastic as a pollutant in the marine environment and offers a broad overview of plastic pollution in the sea. It reviewed the problem of marine plastics and developed a dynamic MEFA by preliminary models on the mobilization and accumulation of plastics in the marine environment. First, a bibliographic search was carried out and it was classified into seven categories according to the most important topics found. From this review, a research work that analyses current management strategies was obtained. Most of the papers are about management measures on land to prevent the plastic's arrival in the marine environment. The citizen campaigns for the elimination of plastics and various national and international projects stand out among other strategies. Although these are fundamental to face the problem of plastics, few studies or strategies have been found. Improving the knowledge about the methodologies and techniques for studying micro/nanoplastics will help to define better strategies. In addition, the review provided knowledge of the main sources and sinks of plastic into the ocean. Therefore, it was collected that the land source represents 80% of the plastic inputs to the sea and the seabed, which is a large sink (most of the plastic waste in the marine environment is settled to the bottom of the seafloor). Information was obtained on the transformations that plastics undergo in the sea (degradation and fragmentation) even though the marine environment is not a means of disposal, but of accumulation.

This chapter has demonstrated the usefulness of the model to study dynamic problems. The dynamic problem studied with the model was the accumulation of plastics in the marine environment: once plastics enters to the ocean, they distribute in different media. Four phases of a dynamic model that represent the mobilization of plastic in the ocean were developed, progressively increasing the complexity. The model showed that plastic debris in the form of macroplastics, microplastics and secondary microplastics in the ocean continues to increase over the years, mostly in the water column. Most of it ends up being accumulated on the sea floor, but the plastic's increase in the water column causes at the same time the increase of plastic in living beings, also affecting humans. The developed model described well the real system trends in the different media. The model was sensitive to parameters that can be modified to consider other possible scenarios: plastics index entry into the ocean, macro and microplastics rate, the half-life of macroplastics to microplastics and the number of fish in the ocean. Adapting and adjusting the model can predict future trends in plastics. Being modelling a useful tool to support new regulations and strategies to deal with the problem of plastic waste.

This chapter has expanded knowledge about the real problem of marine plastic debris pollution around the world.

Finally, to the main conclusion of this thesis it was observed that the tools used in each chapter were valid to minimize the impacts generated in the human activities related to the sea. Furthermore, all chapters contributed to a greater or lesser extent to the regenerative economy. On the one hand, they contributed to reducing the impacts generated by the fishing sector and the processing of its products, which helps to use resources extracted from the sea in a more sustainable way. On the other hand, the analysis of enjoyment activities was essential to reduce the impact on both the manufacture and use of recreational equipment. Finally, the analysis of the recovery of waste generated in the fish and seafood transformation activities, the knowledge of the materials that cause the most waste in fishing (nets) and the prediction of the movement of plastics in the sea, provided information that allowed us to anticipate and minimize the problem of marine pollution. Therefore, this thesis contributes to protecting and obtaining a cleaner and more sustainable ocean.

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ANNEX I: DIFFUSION OF RESULTS

PUBLICATIONS IN SCIENTIFIC BOOKS AND JOURNALS

García Rellán, A.; Vázquez Brea, C.; Bello Bugallo, P.M.; 2018. Towards sustainable mobile systems configurations: Application to a tuna purse seiner. Science of the Total Environment. Vol. 631-632; Pp. 1623-1637. DOI: <https://doi.org/10.1016/j.scitotenv.2018.03.133>.

- Authors affiliation: Department of Chemical Engineering, Universidade de Santiago de Compostela, Av. Lope Gómez de Marzoa, s/n, E-15782 Santiago de Compostela, Spain
- Contribution of the doctoral student: contribution to development of the research, data curation, conceptualization and writing and editing the paper.
- e-ISSN: 1879-1026 ISSN: 0048-9697
- Year of Publication: 2018
- Rank by Journal Impact Factor (JIF), (2018):
 - o Impact Factor: 5.58
 - o JIF Quartile: Q1
 - o JIF Percentile: 89.44
 - o JIF Rank: 27/251
 - o Category: Environmental Science (SCIE)
- Rank by Journal Citation Indicator (JCI), (2018):
 - o Journal Citation Indicator: 1.49
 - o JCI Quartile: Q1
 - o JCI Percentile: 91.75
 - o JCI Rank: 25/297
 - o Category: Environmental Science (SCIE)
- Number of times cited: 0 (Web of Science); 1 (ResearchGate)
- Readers: 47 (Science Direct)
- Authorization of the journal/publisher for the use of the publication in the doctoral thesis. URL: <https://www.elsevier.com/about/policies/copyright/permissions>

Bello Bugallo, P.M.; García Rellán, A.; Barros Frieiro, C.; Cristóbal Andrade, L.; 2018. Mussel Shells' thermal valorisation and odour emissions; Editors: Brooke Mansom, Ellie Grover. Mussels: Characteristics, Biology and Conservation. Pp. 1-32. Editorial: Nova Publishers.

- Authors affiliation: Department of Chemical Engineering, Universidade de Santiago de Compostela, Av. Lope Gómez de Marzoa, s/n, E-15782 Santiago de Compostela, Spain
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Zapelloni, G.; García Rellán, A.; Bello Bugallo, P.M.; 2019. Sustainable production of marine equipment in a circular economy: deepening in material and energy flows, best available techniques and toxicological impacts. Science of the Total Environment. Vol 687; Pp. 991-1010. DOI: <https://doi.org/10.1016/j.scitotenv.2019.06.058>.

- Authors affiliation: Department of Chemical Engineering, Universidade de Santiago de Compostela, Av. Lope Gómez de Marzoa, s/n, E-15782 Santiago de Compostela, Spain
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 - o JIF Quartile: Q1
 - o JIF Percentile: 91.89
 - o JIF Rank: 22/265
 - o Category: Environmental Science
- Rank by Journal Citation Indicator (JCI), (2019):
 - o Journal Citation Indicator: 1.60
 - o JCI Quartile: Q1
 - o JCI Percentile: 94.21
 - o JCI Rank: 18/302
 - o Category: Environmental Science (SCIE)
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- Readers: 134 (ScienceDirect)
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García Rellán A.; Vázquez, Ares, D.; Vázquez Brea, C.; Francisco López, A.; Bello Bugallo, P.M.; 2022. Sources, sinks and transformations of plastics in our oceans: Review, management strategies and modelling. Science of the total environment. Vol. 854; P. 158745. DOI: <http://dx.doi.org/10.1016/j.scitotenv.2022.158745>.

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 - o Category: Environmental Science
 - o JIF Quartile: Q1
 - o JIF Percentile: 90.7
 - o JIF Rank: 26/275
- Rank by Journal Citation Indicator (JCI), (2022):
 - o Journal Citation Indicator: 1.68
 - o Category: Environmental Science
 - o JCI Quartile: Q1
 - o JCI Percentile: 94.16
 - o JCI Rank: 20/334
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PROCEEDINGS IN THE INTERNATIONAL CONFERENCES

Bello Bugallo, P.M; García Rellán, A.; Taboada Gómez, M.C.; Magán Iglesias, A.; Blanco Cid J.M; Identificación dos fluxos mellorables nun atuneiro de cerco e propostas de alternativas. XVI Foro dos recursos mariños e da acuicultura das rías Galegas. O Grove (Spain). October 10-11, 2013.

García Rellán A.; Taboada Gómez, M.C.; Robleda Prieto, G.; Bello Bugallo, P-M.; Blanco Cid, J.M.; Towards sustainable mobile systems configurations: application to a tuna purse seiner. World Resources Forum. Davos (Switzerland). October 6-9, 2013.

Bello Bugallo, P.M.; García Rellán, A.; Taboada Gómez, M.C.; Vergara Rodríguez, R.; Magán Iglesias, A.; Improvable flows identification: application to a tuna purse seiner. WasteEng14. Rio de Janeiro (Brazil). August 25-28, 2014.

Zapelloni, G.; García Rellán, A.; Bello Bugallo, M.P.; Sustainable production and use of marine equipment: a circular economy prospective. WasteEng18. Prague (Czech Republic). July 2-5, 2018.

Vázquez Ares, D.; García Rellán, A.; Vázquez Brea, C.; Bello Bugallo, P.M.; Plastics in our Oceans: Management strategies and modelling. XXV Encontro Galego-Portugués de Química. Santiago de Compostela (Spain). November 20-22; 2019.

García Rellán, A.; Vazquez Ares, D.; Bello Bugallo, P.M.; Management strategies based on multimedia modelling of the fate of plastics from the ocean. WasteEng 2020. ONLINE. May 31 – June 04, 2021.

García Rellán, A.; Yesodharan, V.; Bello Bugallo, P.M.; Sustainable Fishing nets production from residual biomass. WasteEng 2020. ONLINE. May 31 – June 04, 2021.

Yesodharan, V.; García Rellán, A.; Bello, Bugallo, P.M.; Redes de pesca Biodegradables a partir de biomasa residual. XXIII Foro dos recursos mariños e da acuicultura das Rías Galegas. O Grove (Spain). October 7-8, 2021.

Francisco López, A.; Yesodharan, V.; García Rellán, A.; Bello Bugallo, P.M.; Preliminary analysis of processes to produce biodegradable fishing nets. Foro dos recursos mariños e da acuicultura das Rías Galegas. O Grove (Spain). October 6-7, 2022.



This thesis analyses human activities around the sea using a life cycle approach for the identification of sustainable techniques to facilitate the path towards a regenerative economy. The first part deals with the sector of fish and seafood industry, the second part deals with activities related to the fishing sector, and the third analyses activities in the marine environment as a place of enjoyment. Material and energy flow analyses allows to identify impacts of resources and wastes, and Best Available Techniques are proposed. Chapter 9 is dedicated to plastics in the sea related to all the previous activities, including dynamic analysis of flows and stocks, through modelling that predicts trends in the behaviour of these compounds.