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Design of a seafood product based on the Life Cycle Management approach

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Abstract

Oysters are a delicacy which many Italians enjoy, and yet the country is far from being one of their main producers. However, there is growing interest in oyster aquaculture in Italy, which has a big potential for expansion. In this context, the present work aims at investigating what could be the future potential impacts of a new oyster-based production chain located in the Veneto region, in Northern Italy, near the city of Chioggia. The farm under analysis already exists and currently farms mussels. The modelled scenario moves from idea that the production will be split, farming at the same time oysters and mussels. The assessment is performed using the LCA approach, with a functional unit of 1kg of oysters ready for the market (cradle-to-gate). Impact calculations were performed with ReCiPe midpoint (H), v1.03. The overall result is that environmental impacts are likely to be very small and mostly due to the impact of consumables, particularly those used for packaging. Data quality shows margins of improvement, especially regarding end-of-life scenarios for material inputs.

Chapter 1: Introduction

1.1 Trends in aquaculture

Fish consumption globally has been increasing steadily since the 1950s. However, it is around 1990 that the trend begins to show a significant split in its composition. The share of fish consumed globally coming from aquaculture begins to rise extremely rapidly (*Figure 1*). In the period 2011-2015, aquaculture production has risen on average of 5% per year (FAO, 2021). At present, the majority of fish supplied in the world comes from some sort of farming rather than wild capture. This trend pairs with a generalized decline in global fish stocks (RAM, 2021).

In 2019, global production of fish from capture showed a decreased of 4,3% compared to 2018, while aquaculture saw an increase of 3,7% for the same period. Regarding sales, aquaculture confirm this trend, accounting for approximately 64% of total revenue (FAO, 2021). Data confirms an increasing interest worldwide, although different areas have specialized in different products. The enormous growth in aquaculture is mostly due to China, that now is the largest producer of farmed seafood (FAO, 2021).

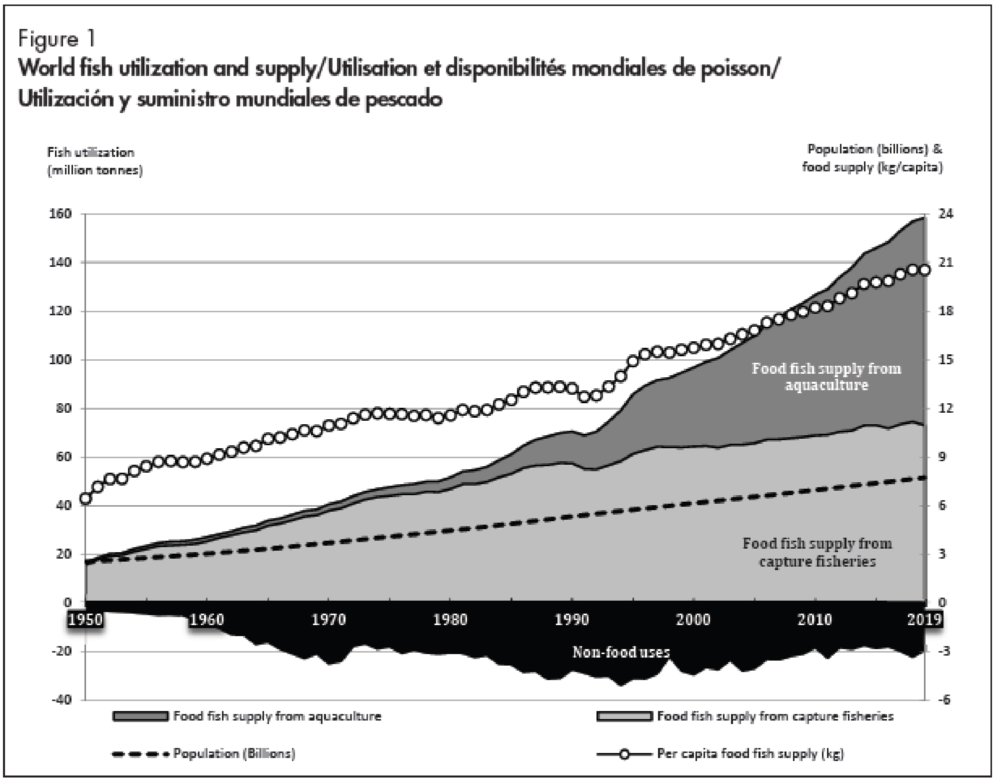


Figure 1 - Fish production by origin, FAO

Aquaculture has received considerable attention in European Union as well, where it is part of the blue growth strategy. In particular, the development of sustainable aquaculture is at the centre of the common fishery policy (EU, 2019). In this context, there is much interest in assessing the environmental impacts of aquaculture, which have been greatly debated and investigated for long time and not only in Europe (Yoshio

Sugawara, 1991). From intensive, inland farming to intensive sea-based farming, the various types of aquacultures are a topic of continuous investigation. This works places itself within this discussion, modelling the possible impacts of a new oyster aquaculture production in the Lagoon of Venice, in Italy.

Italy is one of the biggest consumers of oysters in Europe (European Market Observatory, 2019), together with France. However, while France is the largest European producer, the total oyster production in Italy is comparatively negligible. There is much room for growth in production. Reasons for the lack of facilities are various, not all of them certain. Among them, the increasing competition of cheaper productions, lack of support and difficulty to spread the existing expertise (Cataudella, 2011). Italy remains a big producer of mussels and clams, but potential for expansion of oyster farming is big. Furthermore, Italy has an historic tradition of oyster farming.

1.2 Oyster farming in Italy

Preserved vases dating I-III century A.D. show oyster farms and farming practices similar to suspension systems in use today (Cataudella, 2011), tracing oyster farming's origin back to Roman times. Even sooner, approximately I century B.C., the Latin author Plinius describes an oyster farm in present-day Campania, at lake Fusaro. The area was managed and farmed by a Roman farmer that experimented with natural local oyster beds to increase yields. The experiments were successful, and the Campania region remained known to produce oysters well into the 18th century. During the transition period from Roman to Medieval times, oyster farming was more formally regulated since farms grew rapidly in numbers.

Around 1850, French farming practices were imported in Italy, and it is during this time that modern Italian oyster farming is said to be born (Cataudella, 2011). At the end of 19th century, oyster farming achieved its highest levels of productivity and gained significant interest, which led to the creation of numerous farms from Taranto in the South to Friuli Venezia Giulia in the North. Yet, the interest for oyster farming would not survive the first World War. In fact, during the years that followed it, oyster farming knew a period of stagnation, while mussel farming grew of importance and of quantity.

This trend persisted well into the 20th century, and it is confirmed by present-day data. In recent years, mussel production was more than a thousand times larger than that of oysters (Bronzi P., 2011). However, oyster production has known a steady increase since 2009 and in 2016, the Italian oyster production amounted to 254,25 t (Giovanardi, 2018), while France, the largest European producer, produced in the same year 69.410 tons of oysters (FAO, 2021). The landscape of Italian producers is quite fragmented, and numbers are very small. Production facilities are mostly located in Sardegna and Veneto, with a handful more present in Sicilia, Puglia, and Friuli Venezia Giulia (Bronzi P., 2011).

Natural oyster beds were once present in the Veneto region and in the Lagoon of Venice as well. Due to poor reef management, however, the natural population declined close to extinction. The MAREA project – better described in chapter Materials – aims at restoring a natural reef of European flat oysters (*Ostrea edulis*) in the Lagoon of Venice.

1.3 Scope of work

The basis of this current work is a restoration project organized by Dr Camilla Bertolini, PhD, in cooperation with the Department of Environmental Sciences, Informatics and Statistics (DAIS), Ca' Foscari University of Venice and called MAtchmaking Restoration Ecology & Aquaculture (MAREA). The restoration project has won a Marie Skłodowska-Curie grant (number 886037) and is predicted to last until June 2023 (Ca' Foscari University, 2022).

The MAREA project has two main objectives. Reintroducing oysters of the species *Ostrea edulis* to the Lagoon of Venice is the first main goal. *Ostrea edulis* used to be abundant in the Lagoon, but bad resource management and overfishing have driven numbers down. A similar phenomenon has happened all across Europe (J. Haelters, 2009). The reintroduction site was placed close to mussel aquaculture farms to prevent trawling and dredging from damaging the newly settled colonies. This way, the project will also investigate whether there is compatibility between mussel aquaculture and oyster restoration, while the new reef would be more protected.

The second goal of the MAREA project is the creation of a local production chain based on oyster farming. The seed for this production chain would be collected from the restored natural population, avoiding the need of purchasing it from hatcheries, thus reducing the overall environmental impacts relative to production and transportation of the seed, as well as employing a locally-adapted, sustainable oyster population. The new production chain should also stimulate local oyster demand, broadening the market and increasing consumers' interest.

The project is part of the Native Oyster Restoration Alliance (NORA), a network of restoration projects carried out all over Europe (NORA, 2017). MAREA partnered with another institution part of the network, Dubrovnik University, to source the seed to be used in the project (*Figure 5*). The University of Dubrovnik is working in the Mali Ston Bay in Croatia, providing *Ostrea edulis* seed and brood stocks to other restoration projects in the network. In particular, due to the geographical closeness to Venice, the seed from Croatia was of particular interest, since it would maintain the Adriatic genetic pool.

Figure 2 - Oysters supplied from Mali Ston

The restoration module of the project started with the sourcing of Croatian oysters. Individuals of one to two years of age were transported from Mali Ston to Venice and then studied and placed in the selected location in the Lagoon of Venice, close to Chioggia (VE).

The following step of the project is to study which are the best seed collection sites given local currents and tides. During this stage, collectors are placed in different locations to study variations in yield and identify and document best practices for collection. Additionally, the collection process offers the opportunity to investigate larval dispersal and use the direct data to develop a forecasting model. Both scopes of research of this stage of the project are relevant not only for academic research, but also for the envisioned production chain, considering that at present there is no local knowledge on seed collection nor farming starting from natural reefs. The collection efforts will shed a light on whether a natural reef could be restored below mussels' farm. Finally, the research will proceed with the development and study of energy and growth models for individual oysters.

This current work supports the second stage of the MAREA project: envisioning and modelling a new production chain for local oyster farming. It contributes to the MAREA project by modelling a first draft of production chain and assessing its projected environmental impacts. The environmental impacts are assessed using Life Cycle Assessment approach (cradle-to-gate), and calculations are performed using the software program SimaPro under version 9.0.0.49. The Impact Assessment analysis was performed using ReCiPe 2016 Midpoint (H) V1.03 / World (2010) H. Results and discussions are reported respectively in Chapter 4 and Chapter 5.

The present work starts by introducing the oyster species *Ostrea edulis* from a biological point of view. Research on oyster farming and oyster production supplied the material for the modelling of the production plant, while a visit to the mollusc depuration plant in Chioggia provided precious information on molluscs' value chains. Finally, first-hand information on the production chain were given by the other NORA project, Mali Ston, and were used to fine-tune both the model as well as the life cycle inventory.

After the development of the model, a life cycle assessment analysis was performed to investigate an approximation of projected environmental impacts of the oyster farming system. The analysis started with the identification of the system boundaries and the creation of a life cycle inventory. In this step, information was taken from literature, as well as from direct data provided by another local oyster farm in Veneto and the Mali Ston project. Then, the life cycle modelling and impact assessment were conducted by using the SimaPro software.

The original blueprint of the project included the development of a final product and an estimate of its cost to final customers. However, I was unable to perform this latest step due to lack of information on costs along the production chain at this stage of modelling. This issue will be further discussed in the interpretation section.

Chapter 2: Materials and methods

2.1.1 Life Cycle Assessment (LCA)

Life Cycle Assessment, usually indicated as LCA, is a methodology that aims at assessing the environmental impacts of a process or good (ISO, 2006). A full LCA covers the entire life cycle of the subject of the study, starting with material extraction, and ending with the final disposal. The end-of-life treatment includes material recycling if needed. Life cycle assessment has various applications, among which are the identification of hotspots in the life cycle of a product, the contribution analysis of each step in the life cycle to the overall environmental impacts of a product or process, and the comparison of impacts of different products (ISO, 2006).

LCA was created originally in the field of industrial applications, but was later extended to other fields, including agriculture and food production (X.P.C. Vergé, 2012). During the nineties, it was used for aquaculture for the first time and, since then, has acquired progressively more relevance in this field (P.J.G. Henriksson, 2012). In recent years, policy making has taken notice of LCA and is employing it progressively more in environmental regulations, while companies are adopting this methodology to assess the impact of their products, as a result of stakeholders' pressure (PRé, 2016).

The ISO standards ISO 14040 and ISO 14044 are the main international recognized standards for LCA. ISO 14040 defines a framework for LCA, while ISO 14044 lists more practical requirements to conduct the assessment. However, it is not possible to get an ISO certification according to any of the two standards. Moreover, the way in which both standards are written is quite vague, which has led different organizations to try to harmonize existing practices and provide more detailed guidance to LCA practitioner.

An example of this efforts is that conducted by the European Commission. The European Commission has worked with the Joint Research Centre on a guidance document for LCA practitioners since 2005 (European Union, 2022). This effort led to the creation of the ILCD, International Life Cycle Data Handbook, a book aimed at complementing the ISO standards and helping LCA practitioners. Together with the book, the Joint Research Centre (JRC) of the European Union has produced a series of accompanying guides and documents (European Union, 2022). The full list of documents was specifically developed for LCA practitioners to harmonize different approaches and provide relevant quality criteria.

A different harmonization effort has been conducted by trade organizations, which produced their own Product Category Rules (PCR) to define stricter guidelines for LCA calculations (PRé, 2016). Product Category Rules are based on ISO standard 14025, and are guidelines specific to a certain product category, which is a group of products with similar features (ISO, 2006). They are more prescriptive than the general standards ISO 14040 and ISO 14044, and define very practical requirements, such as the functional unit to be used or the main impact categories. PCRs cover a wide array of product categories, ranging from malt beer to cosmetics to air conditioning and many more (The international EPD System, 2022).

More generally, ISO 14025 defines the procedure necessary to obtain a Type III environmental declaration (ISO, 2020). Type III environmental declarations are more commonly known as Environmental Product

Declarations, or EPDs. EPDs are documents that provide information on the environmental impacts of a product. They are created using PCR. While PCR are guidelines on LCA procedures, an EPD is the final product of the assessment process. A Type III declaration is purposefully intended to be used in the business context but can be used to communicate with customers as well.

There are two more environmental declarations available to business: Type I and Type II (ISO, ISO environmental labels, 2018). Type I declarations are environmental labels that can be awarded by an independent organization. They indicate that the awarded product is preferrable under environmentally-friendly criteria rather than other product alternatives and are aimed at end consumers. For example, under this category fall the German Blue Angel or the natureplus certificate. Type II declarations are declarations prepared by and stated by the manufacturing or retailing company and serve to highlight a specific environmentally-friendly feature of a product. This declaration does not require third-party verification. Overall, the ISO series 14020 – to 14027 – covers the topic of environmental declarations and provides guidance to businesses, organizations, and practitioners.

In this context, the European Union moved to define a less confusing set of declarations that would support both single companies that wish to advertise their products and customers in their purchasing choices. Therefore, a pilot project was launched in 2013 to use Product Environmental Footprint and Organisation Environmental Footprint to measure and communicate on environmental performances in the entire European Union (European Commission, 2013). The pilot period lasted from 2013 to 2018 and involved more than 280 companies and organizations. In 2018, the European Commission has started extensive consultations to define how to draw policies based on such Environmental Footprint tools.

The results of the pilot phase include the testing of processes to define common PCRs. The product categories under study were: batteries and accumulators, decorative paints, water supply pipes, household detergents, intermediate paper product, IT equipment, leather, metal sheets, footwear, photovoltaic electricity generation, stationery, thermal insulation, T-shirts, uninterruptible power supply, beer, coffee, dairy, feed for food-producing animals, marine fish, meat (bovine, pigs, sheep), olive oil, packed water, pasta, per food (cats and dogs), and wine. Out of these, the PCR on marine fish, meat, coffee, and stationery were discontinued (European Commission, 2013).

The most significant in the context of this present work is the PCR on marine fish, which was, however, not completed by the working group (EU, 2016). The scope of this PCR was fish for human consumption, either from fisheries or from aquaculture. This guideline, however, did not cover molluscs of any kind. The pilot was not completed, since the Steering Committee was not able to finish according to the guidelines in time (Norwegian Seafood Federation, 2016). Even with a more generous deadline, the Technical Secretariat denounced the lack of secondary data which caused the greater part of the delay. However, the Technical Secretariat stated that it would start working on a Life Cycle Inventory Database for marine resources production systems in order to cover the gap.

Within the wide array of PCRs and EPDs, there is currently none dedicated specifically to molluscs farming and mollusc farmed products, as far as knowledge by the author goes. This work is, therefore, not based on an existing guideline for aquaculture molluscs products, nor on any draft or working paper, since there is none available, but rather on the perused existing material on performing LCA and scientific papers on aquaculture LCA.

2.1.2 Performing LCA

The LCA methodology includes four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation, all of which contribute to modelling and assessing the overall environmental impacts of a product or service (ISO, 2006). Each phase is crucial to the final result, but two stand out for their relevance and difficulty: goal and scope definition, since it influences the entire analysis, and life cycle inventory, because it requires data collection. Data collection is, in fact, one of the most laborious stages of the entire process.

2.1.2.1 Goal and scope definition

The model under analysis is defined during the first stage of the assessment, goal and scope definition (ISO, 2006). Models are simplifications aimed at describing a more complex reality. Thus, the assumptions and simplifications made during the modelling process are crucial and can alter the final results, and therefore must be clearly stated (P.J.G. Henriksson, 2012). LCA practitioners are generally advised to design all models considering this issue and minimizing influences on the end results. Some guidelines, such as the ILCD handbook, provide helpful instructions to practitioners and are designed to support them in all stages (EU Joint Research Centre, 2010).

The goal definition steers the entire analysis (EU Joint Research Centre, 2010). Under this stage fall the definition of target audience, intended application of the end results, list of limitations from the method, impacts covered, and reasons for conducting the assessment. The boundaries defined at this stage guide as well the quality assessment and checks that will be performed over the study. The target audience influences the structure and choice of reference unit (see below functional unit), for example a consumer-oriented study will pick a reference unit that a general audience can grasp, like a kilogram of meat or a half-litre glass bottle (PRé, 2016). The methodological limitations are extremely relevant from the scientific point of view. As mentioned, models are simplifications of a complex reality and the assumptions made during their development must be clearly outlined. This way, the study can be easily reproduced, tested, and results double-checked, but also improved upon (EU Joint Research Centre, 2010).

Next comes the scope definition phase. It is at this stage that the actual object of the analysis is properly defined (EU Joint Research Centre, 2010). Based on the defined goal, the practitioner defines the reference unit of the study, called the functional unit, and the boundaries of the model, called system boundaries. The functional unit is the unit of reference against which the environmental impacts are measured and is a fixed quantity of the product or service under research (ISO, 2006). It offers a means to quantify and relate the impacts of the object under study to a concrete and easy-to-grasp unit of measure. Furthermore, the functional unit is fundamental because it allows comparisons between impacts of different products or between different production processes of a single good. The purpose of the study dictates the choice of functional unit. In the context of aquaculture, an example of functional unit can be a ton of live fish at the farm gate.

A functional unit is defined by two components: the amount of reference and the level of the life cycle included. In the example, the amount of reference is one ton of live fish at the farm gate. This final part of the definition refers to the system boundaries and signals the scope of the research. Within the boundaries fall all processes and steps that are included in the study, as well as the period of time under research. Since production processes are overly complex, it is not mundane to define when a step is to be included or not. It is also easy to find loops that could prevent the analysis to be effective. Let us take the example of mineral extraction, for example coal. After extraction, coal has to be transported away from the mine and to cargo ships or other means of transport. To reach the shipping centre, coal is transported, for example, on a truck. But to produce this truck, coal was used to power machinery or electricity generators, and so on. In order to simplify the analysis and make it effective, the system must be subject to boundaries, that can, for example, include capital goods production and disposal, use phase of product or service, or disposal of used product. Usually, a graph is used to show the boundaries of the system and all the processes that fall within.

Figure 2 illustrates different definitions of the system boundary, each including a different number of steps in the production process. LCA studies can be gate-to-gate, meaning they consider solely the actual production of the good, cradle-to-gate, which include extraction of materials used in the production process, or cradle-to-grave, full LCAs that include all stages of the life cycle, from material extraction, to use phase, to end-of-life management.

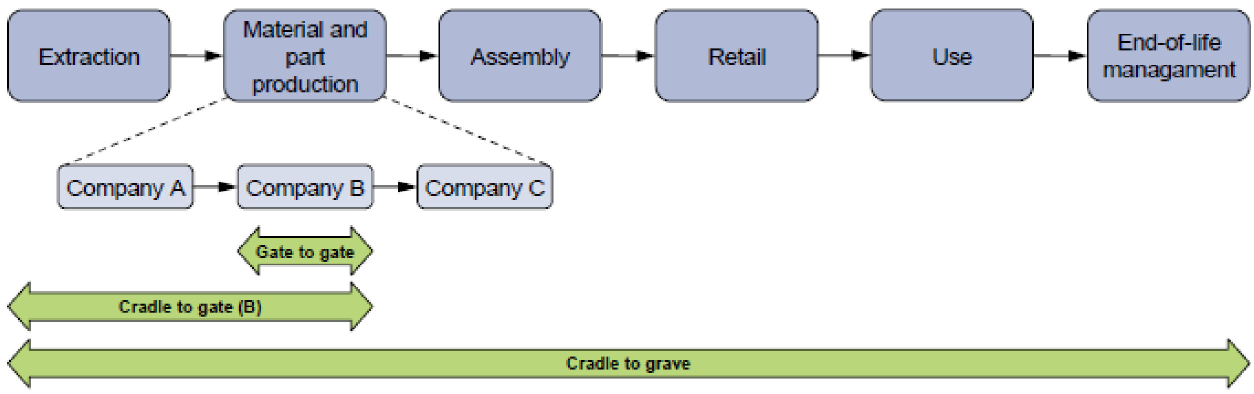


Figure 3 - Overview of different system boundaries

The scope definition phase includes more steps, such as the definition of deliverables, types, sources and quality of data, impact assessment requirements and, if applicable, provisions on peer review. Additionally, in this phase the practitioner defines if consequential or attributional modelling are used. These two forms of modelling are needed if the process that is being analysed produces more than one output. For example, cow farming produces either milk or meat, depending on the scope of the farm, but also leather and manure. These outputs are to be separated and a procedure on how to account for the attribution of inputs to different outputs is to be described.

Consequential modelling is usually used to assess and compare variations from a baseline level, and as such is a model that presents switches. For example, this type of modelling can be used to check the different impacts of the end product when two different inputs or processes are adopted – and could be the base for decision-making in a company.

Attributional modelling, instead, is usually employed to assess hotspots in the life cycle of a product or service. If the process has more than one output, the impacts of inputs and outputs are weighted among the final products. This process is called allocation. Allocation can be performed based on a physical quantity, like mass or energy. In this case, the inputs are allocated with respect to the share of the physical quantity represented by the functional unit (*Figure 3*). For example, let us consider again cow farming and the two outputs meat and manure. Let the functional unit, our main goal, be one kilogram of meat, and the second sub-output manure. One of the main inputs in this instance is feed, and in the attributional modelling we have to assign the quota of feed that ends up contributing to the main output meat and the one that contributes to the sub-output, manure. Finally, let the output be 20:80 meat to manure (this is a purely fictional example). If the study uses allocation by mass, within the time period under study, each input has to be scaled down to the percentage represented by the output of reference. In this case, since the study assesses meat, the inputs have to be multiplied by 0,2 that is the ratio of total output represented by meat. Allocation can also be performed based on revenue, and inputs are weighted based on the economic value of each co-product.

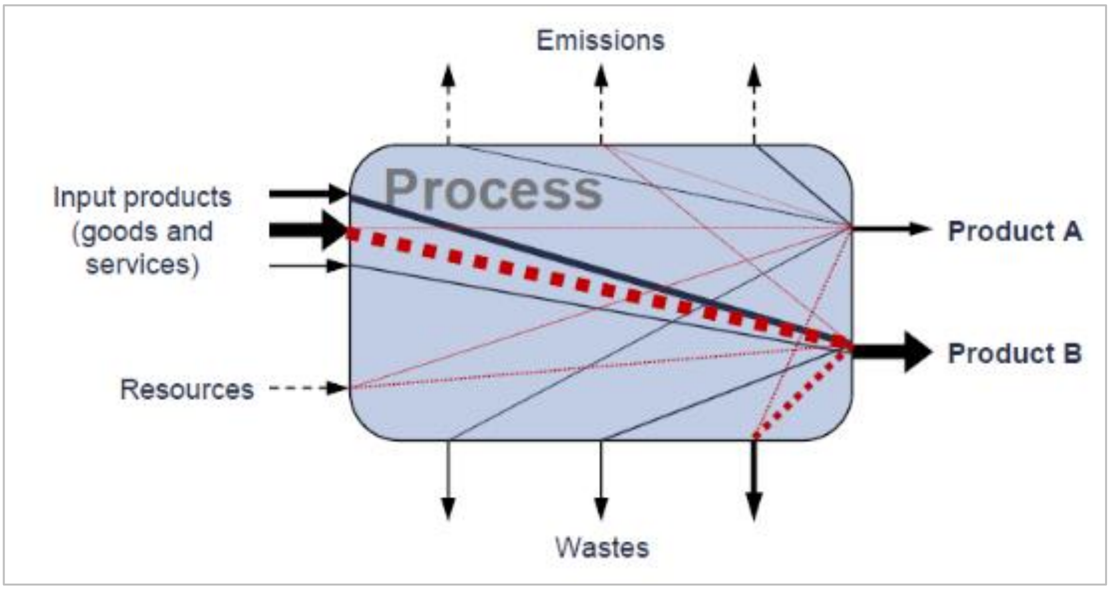


Figure 4 - The thickness of the lines represents the allocation percentage to each output, here Product A and Product B.

2.1.2.2 Life cycle inventory

The next phase of LCA is the inventory. The inventory phase requires data collection and is, as such, very time consuming. Data requirements in this phase include both foreground and background data. While foreground data are data relative to information specific to the system under study – the actual product or process – background data refers to data relative to all generic inputs used in the production, like electricity generation, transportation, and waste management. The definition of which data fall under the foreground category and which under the background category depends on the subject of the analysis. For example, when carrying out the analysis on corn farming, it is not necessary to acquire full information' on tractors used in the production, but a general tractor proxy might do. Instead, if the subject of the LCA study is the production of a tractor, this approximation is no longer valid and data requirements for the production of the tractor will rise significantly.

The collection of primary data requires the involvement of data providers, which include data owners, product manufacturers, or service providers. This step can be challenging since confidentiality issues may arise. Data collection can also be complicated by terminology issues or by actual data availability. Primary data are always to be preferred, despite the challenges represented by collection, since they better describe the process at hand. Background data can fill gaps and offer a comparison and can be acquired from databases or literature research.

2.1.2.3 Life cycle impact assessment

After all data have been gathered, the analysis proceeds with the life cycle impact assessment. This stage evaluates the actual impacts of the life cycle of the subject of the study according to precise impact categories. Impact categories relate the inventory to impacts on human health and the environment. The impact assessment categories should be defined during the preliminary stage of goal and scope definition and be relevant for the product category under study. As such, they can be found in PCRs. If a process or product has no own guidelines, the practitioner can refer to the literature to identify the most relevant impact categories for its research.

Environmental aspects are the key target of LCA, but there is growing interest currently in social assessment (Nathan L. Pelletier, 2007). There are documents or initiatives that do provide some kind of guidance on social instances of relevance, for example the UNEP SETAC Guidelines for Social Life Cycle of Products (UNEP, 2018), but no actual LCA guideline exists at present that are sector-specific. As such, defining social impact assessment remains still an exercise.

Existing indicators describe and assess the intensity of impacts of a given product with respect to the functional unit and the final quantity of output. This could result in higher impacts being offset by higher yields, reducing the informative value of the impact assessment results (X.P.C. Vergé, 2012). These difficulties call for the definition of a broader picture and a clearer overview of the full impacts of the production processes under analysis.

The standard ISO 14040/44 defines mandatory and optional elements of the assessment. The mandatory elements are classification and characterization, while the optional ones are normalization, ranking, grouping, and weighting. Classification is the process of assigning to each input and flow its contribution to each environmental impact categories. This is necessary because one input can, for example, contribute to more than one impact category. Moreover, different inputs can act on a single impact category.

When different substances have an effect on a single impact category, they can do so in significantly different ways. Let us take the example of greenhouse gases and their global warming potential. The Kyoto protocol, updated after the Doha round, lists seven greenhouse gases to be reported by signing parties – a list that is also taken for reference for carbon equivalent accounting for companies. But the seven gases in the list have quite different global warming potentials. Methane, for example, has twenty-eight times the global warming potential of carbon dioxide. In this case, impacts have to be made uniform using characterization factors. In the case of climate change impact category, IPCC equivalency factors can be used.

The results of this first impact evaluation can be difficult to interpret: they are expressed in units that are hard to grasp immediately, like CO_2 equivalents or P equivalents. Results can be made easier to interpret by using normalization and weighting. Normalization is the process of referring the results of the impact assessment to a reference level, thus making it easier for readers and practitioners to interpret whether a result is high or low. In order to carry out the normalization, however, the researcher must define the reference level, which can be a benchmark quantity found in literature. Since this is a subjective step in the analysis, normalization is an optional step under ISO 14040/44.

Weighting serves a similar purpose, in the sense that is aimed at easing interpretation efforts. This operation consists in defining a set of weighting factors, each one specific to a single impact category. By multiplying the weighting factor to the results for each impact category, the relative relevance of each impact is obtained. For example, an analysis could put more relevance to eutrophication rather than acidification potential.

While weighting is usually used in internal decision-making, it should not be used when carrying out comparative assessments that are later disclosed to the public, according to the ISO standards. This is mainly due to its subjectiveness. In fact, weighting factors have to be defined and tailored for every study. There are various ways of setting them, calling upon a panel of expert, using the monetarization criteria, or calculating the distance from a specific target. However, all the approaches have some flaws. For instance, panels can have their own intrinsic political view, which can deeply influence the assessment. The targets set are also a result of policy, either governmental or corporate, and usually not provide clear information on whether all targets set are equally relevant. Monetarization, finally, starts from the assumption that all possible costs to remediate environmental negative impacts can be summed up directly, like willingness to pay and present costs, even though this is usually not the case in reality. As a consequence, weighting remains a controversial step of LCA.

2.1.2.4 Interpretation

The last step of any LCA is the interpretation. Interpretation can be performed continuously over the course of the study, to improve the inventory or the model, check for errors, and ensure that the analysis follows the goal defined during the preliminary phase. It is also used at the end of the analysis to draw conclusions. In this instance, questions that were opened during the goal and scope definitions should be answered – or the end result should be a recommendation on how to improve future analysis and eventually answer the original questions. This is also the phase where the analysis is assessed for quality criteria, like accuracy and completeness, and that all previous phases are critically reviewed. Uncertainties should be addressed as well at this stage, both regarding data sources or incompleteness, and modelling.

The final results of the LCA can be subject to different analysis to fine tune conclusions and better define results. The first one that can be performed by practitioners it a sensitivity analysis, which seeks to evaluate the influence of major assumptions on the end results. In this analysis, assumptions are modified, and the impacts are recalculated. Core assumptions can greatly influence the results and should be clearly motivated. The sensitivity analysis is used to weigh the influence of its crucial assumption.

Another concluding analysis is the contribution analysis, that focuses, instead, on the relevancy of processes within the life cycle of the product or process under study. This analysis serves to identify the main hotspots inside the system boundaries, which can later be further investigated or be subject to key decisions by policy-makers or managers. Finally, there is inventory analysis. This is an analysis of the final inventory, complete of emissions to natural bodies – water, soil, and air.

2.1.3 LCA software

There is a number of software solutions to conduct life cycle assessment analysis (*Figure 4*). Among them, probably the most wide-known is SimaPro. SimaPro is a software developed by PRé Sustainability (PRé, 2016), created during the nineties. This tool can be used for a range of services, such as carbon or water footprint calculation, sustainability reporting, product design and overall life cycle assessment.

The key feature of each software is the databases that it contains. With SimaPro, researchers can access by default: Agri-food, ecoinvent, European and Danish Input/Output database, US Life Cycle Inventory database, as well as industry data libraries. Additional databases are available on request. In particular, the ecoinvent database contains more than 10,000 processes and was created by different Swiss institutions with the aim to integrate single existing databases. This database has different versions of datasets, six of which are included in SimaPro:

1. Allocation default, unit processes
2. Allocation default, system processes
3. Allocation recycled content, unit processes
4. Allocation recycled content, system processes
5. Consequential, unit processes
6. Consequential, system processes

Figure 5 - LCA software program

"Allocation" means that the datasets have been created following attributional modelling, while "consequential" datasets follow consequential modelling. "Unit" datasets contain details on impacts and resource use starting with one production step in the whole production chain. Meaning, it does not consider the full value chain of the selected input by itself, but SimaPro includes all the missing operations by default. "System" processes are processes that include all emissions from the value chain of a product or process, but that are not linked to other processes. In practice, system processes are resulting from other LCA analysis and as such, are specific to the system regarding which they were carried out. Finally, practitioners can select input/output databases, which are created with reference to a specific economic sector. This feature makes this kind of databases more suitable for larger assessments, covering wider system boundaries, such as entire countries.

A second, extremely relevant feature for an LCA software is the collection of methods to calculate the impacts of the subject under study. SimaPro is equipped with a significant number of impact methods, among which ReCiPe 2016 Midpoint and Endpoint, CML, IPCC 2021, and many more. ReCiPe was first developed by PRé Sustainability, the University of Leiden, the University of Njimege and the National Institute for Public Health and the Environment of the Netherlands (RIVM) in 2008 and has undergone an update in 2016 (M.A.J. Huijbregts, 2017). With eighteen midpoint indicators and three endpoint indicators, the method aims at translating the life cycle inventory into a set of more manageable indicators, representing environmental impacts (National Institute for Public Health and the Environment, 2018). Each scenario, mid- and endpoint, has then three subcategories: individualist, hierarchist, and egalitarian. Each category relies on different assumptions regarding the climate mitigation and adaptation pathways. The individualist scenario is more optimistic, the hierarchist relies on a consensus model, while the egalitarian adopts a precautionary approach (PRé, 2016).

This current work is based on SimaPro PhD, version 9.0.0.49, and uses databases; ecoinvent 3, cut-off by classification, unit and agrifootprint. Ecoinvent was chosen because of its wide range of processes, very useful since the modelling under research covers a production chain that not yet existing. Agri-food, instead, was chosen for its adherence to the scope of research.

2.2 Ostrea edulis

In order to model a brand-new production chain for *Ostrea edulis*, the first step was to research the species. I conducted an analysis jointly with Dr Bertolini to learn the key features of the species *Ostrea edulis*. An overview of the species is presented in *Table 1*.

Category	**Entry**
Scientific name	*Ostrea edulis*
Phylum	Mollusca
Class	Bivalvia
Order	Ostreidae
Genus	Ostrea
Authority	Linnaeus, 1758
Size range (both sexes)	0.2-11 cm
Size at maturity (both sexes)	5 cm
Growth rate	20 g/year
Mobility	Sessile
Feeding method	Active suspension feeder
Diet/food source	Planktotroph
Sociability	Gregarious
Environmental position	Epifaunal
Depth range	0-80 m
Biological zone preference	Lower circalittoral, Lower eulittoral, Lower infralittoral, Sublittoral fringe, Upper circalittoral, Upper infralittoral
Tidal strength pref.	Very weak, weak (<1knot)
Habitat preference	Estuary, open coast, ria/voe, sea loch / sea lough
Substratum / habitat preferences	Bedrock, Cobbles, Gravel / shingle, Large to very large boulders, Mud, Muddy gravel, muddy sand, Pebbles, Small boulders
Salinity pref.	Full 30-40 psu Variable 18-40 psu

Table 1 - Ostrea edulis main characteristics, own elaboration based on (J. Haelters, 2009)

2.2.1 Description and habitat

Ostrea edulis, in Italian *ostrica piatta* or *ostrica europea*, is a bivalve mollusc from the genus *Ostreidae* (*Figure 6*). The genus *Ostreidae* includes sixteen genera and seventy-five species of oysters, all of which breed in a similar way. Oyster embryos are bred inside the pallial cavity, which is the space between the shell and the upper part of the body. Embryos develop inside this cavity until they are released into the water during swarming (B. Colsoul, 2021). At maturity, *Ostrea edulis* reaches approximately 5 cm, and grows yearly with a rate of around 20 g/year (J. Haelters, 2009).

Ostrea edulis is a suspension feeder, meaning that it feeds by filtering the water column. During filtration, food particles are retained by the gills and then used as nutrient. This is also the reason why oysters – and mussels in general – often have to undergo depuration before commercialization: molluscs absorb all sorts of particles from their environment, including pathogens and contaminants, if present in the water (Federcoopesca, AGCI Agrital, Lega Pesca, 2011).

Ostrea edulis naturally creates reefs in coastal and estuarine areas, particularly in sublittoral – that is the area of the seabed below the low-tide mark – and in subtidal areas – areas usually completely submerged that can be exposed during extremely low-tide events (J. Haelters, 2009).

Some existing farming techniques try to mimic these conditions by growing oysters so that they spend part of the day above the water and part of the day below. This is a typical farming method in France, but there is also one oyster farm in Italy which uses this approach (E. Tamburini, 2019). However, this method is mostly used for the species *Crassostrea gigas*, rather than for *Ostrea edulis*.

Figure 6 - Ostrea edulis

Ostrea edulis is distributed from 65° North in Norway to 30° North at Cape Ghir in Morocco. It was naturally found in this area but, most importantly, farmed, as well as exported to North America, Australia, and Japan. It is likely that this transit of adult individuals led to the spread of high-mortality diseases in various farms and populations (B. Colsoul, 2021).

Ostrea Edulis' beds can be found upon muddy fine sand or sandy mud mixed sediments (J. Haelters, 2009). Natural reefs are usually found in low depth estuarine areas, protected by sediments, particularly hard and clean ones. The species is hardly found on muddy sea bottoms and at very low depths, while it has been found in deeper waters and even offshore, for example in the United Kingdom (J. Haelters, 2009). The majority of natural reefs, though, has disappeared over time due to overexploitation. Natural beds are usually made of dead shells, which ensures a hard surface for spat – baby oysters – to attach on to. Many associated species can be found upon oyster beds: species of Ascidiella, sponges, polychaetes (large, suspension-feeding), seaweeds. Materials and objects used for seed collection by farmers try to mimic this natural reef to increase attachment rate.

2.2.2 Reproduction

Ostrea edulis is an asynchronous hermaphrodite, meaning that a single individual can change its sex more than once during a single breeding season. However, the species tends to be male during its first adult phase (B. Colsoul, 2021).

The number of spawning events per year, the intensity of spawning and the spawning period all vary with geographical regions and climatic conditions. The reproductive strategy of *Ostrea edulis* is internal brooding, which is internal incubation of the embryos. After internal larval development, swarming occurs, and larvae are expelled from the mother oyster in clouds. The size of larvae depends on the conditions of incubation, therefore on environmental parameters, food abundancy, and other stressors (B. Colsoul, 2021). Nutritional levels, in particular, play a role in determining the main gender of spawned individuals.

As mentioned, movement of adult oysters for the purpose of farming has led to the spread of diseases (J. Haelters, 2009). But it has also led to the dilution of natural genetic diversity. One of the issues of seed provision is, in fact, lack of proper and geographically-specific genetic pools. As such, the sourcing of oysters for the MAREA project and the modelled production chain in this work takes a step towards maintaining locally-adapted genetic pools (Ca' Foscari University, 2022).

2.2.3 Seed provision

Given the growing interest in oyster restoration as well as aquaculture farming needs, the supply of *Ostrea edulis* seed is currently facing a shortage (B. Colsoul, 2021). The supply is limited both in quantity and quality. A proper supply should increase overall volumes in order to satisfy all its demand queries, while focussing on increasing the genetic diversity of its products. The knowledge about eco-physiological and environmental drivers is still limited for this species and this, in turn, limits the development of successful breeding methods.

Today, the production of seed is both sea-based and land-based (B. Colsoul, 2021). The most commonly employed sea-based method in Europe is wild collection (also called sea-based collection). When following this method, farmers place collectors in the sea before the swarming period to harvest larvae from natural populations. Collected oysters are left to grow up to 5-6 mm, then the collectors are lifted and transferred to the growth area – or the spat is removed and placed in mesh bags (Giovanardi, 2018). This method ensures high genetic variability and has low operating costs, but the production is seasonal and unreliable, since the settlement rates depend on environmental conditions as well as on the period where collectors are put in place. This is one of the most delicate and crucial parts of oyster aquaculture production.

Another sea-based method is breeding polls. They are naturally occurring biotopes, enclosed systems with a depth of around 5-12 m. Given their water and sediment composition, they create peculiar summer conditions with constantly high water-temperatures, which allow for very successful oyster reproduction.

The third sea-based method is breeding ponds, sort of "spatting" ponds. They are enclosed artificial ponds where spatting occurs. Because of their construction, spat remains in the enclosed area and collection becomes easy. This method can support ecological restoration projects and maintain high genetic diversity.

Hatcheries are, instead, land-based. In hatcheries, breeding cycles are mimicked artificially, and spawning periods are made more frequent to provide a steady supply of seed. Hatcheries are of great interest, but there are still some unanswered questions regarding the required parameters necessary for steady spawning occurrences. Furthermore, this method does not provide enough genetic variability.

2.2.4 Stressors

There are two main diseases currently known that are especially deadly and dangerous for oyster populations: Bonamiosis and Marteiliosis (J. Haelters, 2009). Marteiliosis is a disease caused by the protozoan *Martelia refrigens*. Mortality caused by the disease affects particularly 2-year-old individuals and rates can reach up to 90%. Bonamiosis is also caused by a protozoan, *Bonamia ostreae*, and is believed to be originated in the USA. Transport likely occurred when adult individuals were imported in Europe for farming. The parasite affects especially older oysters with mortality rates of 50-80% of the stock. In younger oysters, infection rates have been observed to be lower.

Being filter feeders, oysters are also prone to contamination from metals and synthetic compounds. Different chemicals can have different effects at different development stages of Ostrea edulis. For example, zinc can increase larvae mortality, but other compounds can have different repercussions (B. Colsoul, 2021).

Finally, Ostrea edulis can be eaten by predators. The main ones are invertebrates such as crustaceans, echinoderms and gastropods. Examples of gastropods predators are the Atlantic dogwinkle, the Asian rapa whelk, and the Atlantic oyster drill. Among echinoderms, we find the common starfish, the brown crab, and the shore crab.

Moreover, the species is highly sensitive to variation of the substrate, for instance substrate loss and smothering, and to contamination: synthetic compound contamination, introduction of microbial pathogens or parasites, introduction of non-native species and direct extraction.

2.2.5 Recovery

Since moving adults among geographic areas can result in the spread of serious diseases, the best strategy for the restoration of oyster population is to seed juveniles on beds, be they natural or restored (B. Colsoul, 2021). Another possibility is larval release, but this strategy presents serious risks, since larvae have a low survival rate in the wild, and the places fit for settlement are very few.

Recovery depends on quantity of larvae that are spawned, attach to the reef and then survive to adulthood – the recruitment rate – since adults are permanently attached and incapable of migrating. However, larval production is highly dependent on environmental conditions, as well as on hydrographic regime and the presence of suitable substratum. Spat prefers to attach to adult shells or shell debris. This is also why restoration project usually employ empty shells to prepare a better substrate and increase chances of survival.

Ecological restoration of *Ostrea edulis* is relatively recent and aims at ecosystem function and recovery. One example is represented by the already mentioned NORA network that operates at the European level, with projects going from Spain to the United Kingdom, to Croatia. Major challenges in restoration related to genetic aspects are avoiding transfers of pathogens and diseases, achieving sustainable survival rates, and retaining a high genetic diversity.

2.2.6 Market

Oysters currently produced in Europe come both from farming and wild capture. The main European producer of wild caught oysters is Denmark with 268 tonnes, followed by Spain and Croatia (European Market Observatory, 2019). The European producers in 2019 captured less than 500 tonnes of oysters overall, the majority of which is the native European species, *Ostrea edulis*.

On the other side, in 2019 the EU produced 107,000 tonnes of oysters, mostly *Crassostrea gigas*. The European share covers only 2% of the global market. The European production has increased over the last years, with the main producers being France and Ireland. The main consumers of oysters in Europe are, instead, France and Italy (Giovanardi, 2018) (European Market Observatory, 2019). There is a big market to tap into, as far as oyster demand goes in Italy, while production is almost negligible. As mentioned in the introduction, in fact, production in 2016 – the latest data – was of approximately 254 tons, while in the same year France produced around 69,000 tons.

Broadening the scope, the global production landscape, represented in *Figure 7* (Robert Botta, 2020), is dominated by China.

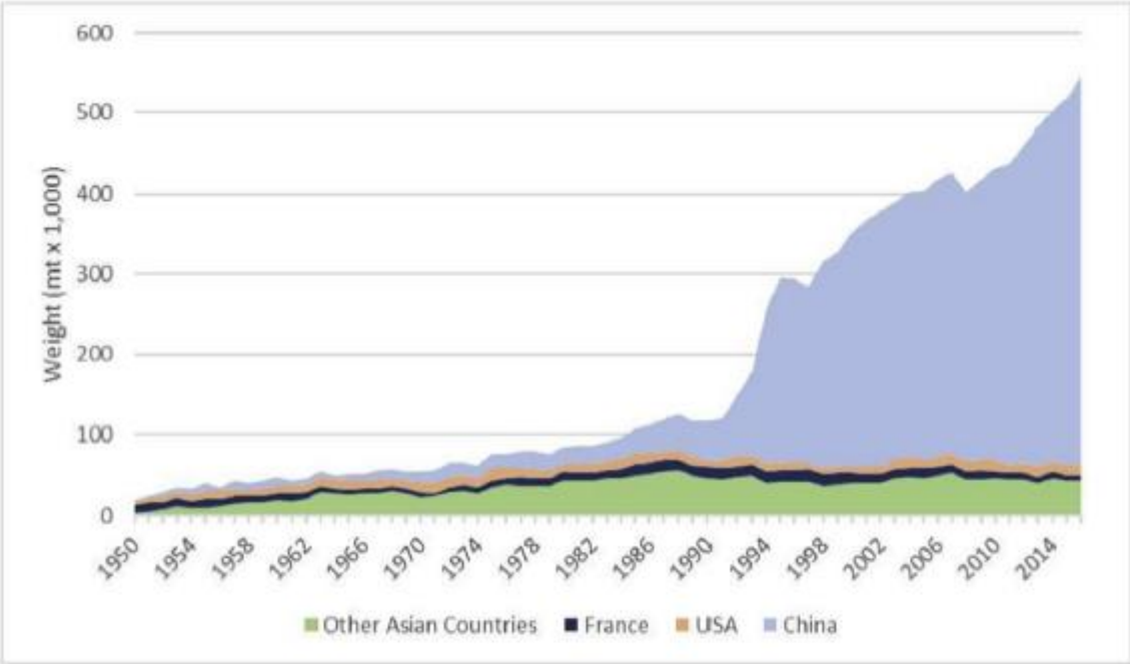


Figure 7 - Market share in oyster production, globally

The quantities farmed by the first producer, in terms of weight, are not even comparable with all the other big producers combined. It is however worth mentioning that France is one of the main global producers at the country-level.

Chapter 3: The modelled production chain[1]

The farm under study is located in Chioggia, a town in the Venetian province (*Figure 8*). The precise location of the farm is: 45°13'47.0"N, 12°15'58.6"E. The farm currently exists today, therefore the modelled infrastructure will not be built from zero in real life. However, the existing plant currently farms mussels. In the model under research, the main idea is that mussels will be farmed jointly with oysters sourced from the natural population restored by the MAREA project. This is the context within which the model has been developed.

Oyster farming follows dissimilar stages than mussel farming, but it is likely that many operations will overlap. For example, juveniles are sourced around the same period (PEI mussels, 2009). Furthermore, mussels need to grow for a shorter period of time before harvest and inspections by the anglers are frequent. These inspections could be used to check on oysters as well, in a cost-efficient fashion.

The success of the restoration project MAREA is the core assumption of this work. I moved from the assumption that the restoration of a natural reef of oysters *Ostrea edulis* in the Lagoon of Venice will be successful and will provide a steady and reliable supply of seed to be employed in the aquaculture farming. Furthermore, my model depicts a steady state situation, where the production chain is already well structured, and ignores the initial set-up years. The quantities considered as well as the material needed are, thus, estimates relative to a mature system.

Figure 8 - Location of Chioggia in the Italian peninsula

[1] The system envisioned made use of discussion with real-time practitioners more than literature. The final model was set up after discussion with Chioggia's plant main veterinarian and a Croatian farmer.

Another core assumption of the project is relative to the actual farming system. In my model, oysters can be farmed jointly with mussels, an hypothesis the MAREA project actually aims at verifying. To make the system a more realistic one and gather first-hand data, I cooperated with the veterinarian that works on the existing mussels' plant, Dr Boffo.

The farming infrastructure in place (*Figure 9*) is very typical for the Lagoon of Venice. Wooden poles are driven into the seabed and make up the core structure of the farm. Steel ropes are suspended between the poles and along the entire length of the farm. From the steel ropes are currently hung the mussels' nets (*calze* in Italian). In the modelled plant, first lantern nets and then ropes (on which oysters are cemented) will be hung from the steel ropes as well.

The Chioggia plant in the lagoon is located close to a *casone*[2], a support structure that serves as warehouse and tool shed. This structure hosts an electricity generator powered with natural gas, needed in the production. Anglers currently travel by boat from the docks in Chioggia to the farm with a small boat and inspect the mussels frequently. The number of trips modelled in the research scenario are not larger than those required currently. The assumption behind this is that farmers will make use of the already established trips to increase cost-efficiency. This is the existing plant onto with the oyster farm will be created.

Figure 9 - Picture of a farming system similar to the one envisioned in my model

3.1 The farming process

Oyster farming follows similar phases for both the main farmed and caught species of oysters in Europe, *Ostrea edulis* and *Crassostrea gigas*. The main production stages are four: seed collection, pre-fattening, fattening, and grow-out (*Figure 10*). During the first stage, seed is either collected from natural population or taken from hatcheries and placed in the water. Oysters are left to grow on various supports in two distinct stages, pre-fattening and grow out. Then, animals are moved onto a final support, where they do their final

[2] Historically, casoni were buildings fabricated by anglers in the Northern Adriatic to serve as a periodic settlement and base camp for fishing. They have become progressively rarer over the course of the years.

growth period. Afterwards, they are ready for collection and processing. The four stages of oyster farming are described into more detail below. The description also includes the adaptation to the modelled setting.

The modelled production phases and periodization has been created with inputs from both Dr Boffo, veterinarian at the plant, and representatives from the Croatian project, who provided information regarding local plants with similar size and farming techniques.

3.1.1 Seed collection[3]

The first stage in oyster farming is the collection of seed. Usually, farms rely on foreign supply of seeds or on seed produced by hatcheries. The modelled plant, instead, will collect seed from the natural population restored by the MAREA project. Collection from natural population will ensure a high level of independence of the Chioggia farm, while at the same time the seed will be better suited to the local climate and water conditions. Since there will be no need for transportation, overall environmental impacts will be reduced as well.

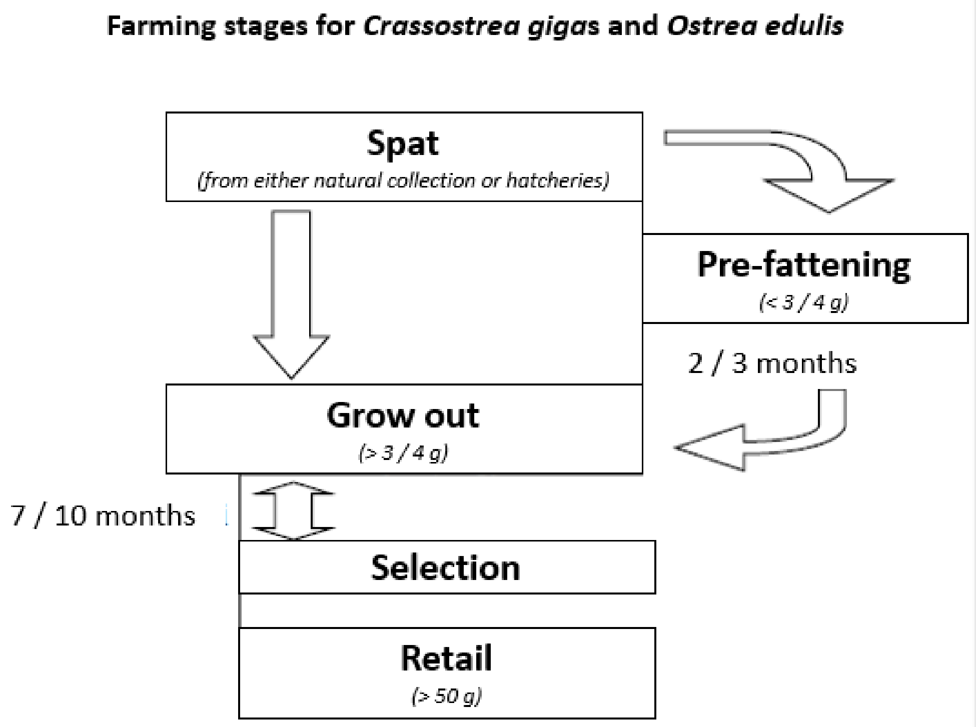


Figure 10 - Stages of oyster farming.

Based on the natural breeding cycles of oysters, seed spawning would occur in springtime from the natural population. The seed can be harvested using different techniques. In the model, farmers will deploy coupelle collectors, also known as "Chinese hats" (*Figure 11*), near the sea bottom in four to five different locations surrounding the natural population's reef. Before being placed under water, collectors are tight together with a rope or rebar in groups. In the modelled scenario, collectors are grouped by five and linked by the rebar bar. The MAREA project has, among its aims, to investigate which collection sites are more favourable based on sea currents. The farm will, thus, benefit from the results of the pilot and pick the best collection spots to maximize yield.

[3] All periodization and time estimates used in this section come from Croatian real-life data.

In order to increase yield, the collectors need to develop a biofilm on their surface in order to be attractive for the larvae. Therefore, they are treated before seed collection occurs. Collectors are placed under water for a 1,5-2 months period, some months before the actual collection begins, and then cleaned and left to dry. After such treatment, they are employed in the seed collection process.

The collection period lasts approximately 6 months. This estimate was obtained from the Mali Ston plant, from real-life data. In the Venetian Lagoon, this period could last less. However, having primary data from an existing plant that farms *Ostrea edulis*, the ultimate assumption was to adopt this periodization as best estimate. After this period, the collectors are retrieved by the farmers, who then move the oysters to lantern-shaped nets for the following production phase.

Figure 11 – Series of coupelle collectors for oysters

3.1.2 Pre-fattening

After collection, spat is moved from collectors to lantern nets (*Figure 12*). These are plastic nets in the shape of lantern, where oysters can grow and, at the same time, are protected from predators. Usually, during this phase oysters are predated by seabream[4] and the nets are intended to protect them in this first grow period.

[4] This precaution was advised by the other NORA project, in Mali Ston. Predation is likely to be less relevant in the Lagoon of Venice, but I incorporated the remark.

Figure 12 - Lantern nets for oyster aquaculture

The pre-fattening phase will last from 2-3 months up to 1 year. I was unable to produce a more precise estimate since the actual duration will depend on the observed predation and growth rates. Once the modelled system will become real and operational, farmers will adjust the pre-fattening period based on local conditions to minimize predation. In an ideal case (low to almost no predation), oysters are grown in lanterns up to 3 – 4g. In the other scenario, they are left much longer, and final size at the end of this stage will be a function of its duration.

Under the high predation scenario, it is possible that the original lanterns would become too small for the oysters over time. In this case, farmers could employ two different sets of lanterns, a small one and a large one, to accommodate for the increased dimensions, or employ adjustable lanterns that can spread apart while oysters grow. My modelled scenario relies on the assumption that predation will be mid to high, therefore I performed my calculations using two sets of lantern nets. The estimated duration of this stage in the calculations is of approximately 10 months.

During this period, farmers frequently inspect the nets to remove fouling and to check on the oysters, ensuring that they are well protected from predation and that they grow steadily. After this stage, oysters are moved onto another structure and are left to grow to their final size before harvest.

In order to better tune the model, I contacted the partner project of Mali Ston, from where oysters were bought. Their predation rate is very high. As such, the longest growth period occurs in lanterns. Under the modelled scenario, the growth period will be almost equal. However, the real system will be adjusted depending on what the actual conditions prove to be and could be less similar to the Croatian scenario rather than the modelled one.

3.1.3 Grow out

Under my assumptions, this will still be the longest stage of oyster production. I estimated the growth period to last approximately one year. Oysters are very slow to grow, and they reach a size suitable for commercialization in around 2,5 years.

During this final stage, oysters are removed from the nets and glued to ropes in pairs using concrete. This is an important operation: oysters need to be spaced properly and handled with care. This method of farming is more expensive than terminating the growth phase in lanterns or cages but ensures the highest quality of the end product. With this technique, oysters have a lot of space to grow, producing generally a more appealing and regular shell.

3.1.4 Harvest and selection

When oysters are fully grown, they are harvested manually. Farmers collect the ropes on the boat and separate them one by one. They are detached from the rope using appropriate tools, cleaned twice and then unloaded at the Mollusc Depuration Centre (CDM). Here, they undergo depuration, if they need so, and a selection process.

Minimum weight for oysters at the end of their growing period is 20g, that corresponds to the lowest possible calibre for *Ostrea edulis*. Oysters' quality is indicated by their calibre, a number that represents their weight. Calibres for *O. edulis* span from 6 (the lowest, 20g) to 000 (highest, 100-140g). There is the possibility to obtain a 0000 calibre, corresponding to extremely big and rare molluscs, but they are rarely caught. Usually, oysters are sold and exchanged starting from calibre 0: 80-90g. This is also the assumption I worked with. In estimating the dimension of sold products, I use the average of 80-90 g[5].

Together with the veterinarian and based on direct data from the other farm in Veneto, I estimated a survival rate of 80% of the farmed product and a final yield of 20160kg of oysters. This quantity can be considered quite high based on levels of the Italian production, which yielded 254 tonnes in 2016. However, they are an estimate necessary for the model. Actual data could prove to be less abundant, but there is no way of knowing it before the actual farming system is created.

3.1.5 Processing

Molluscs are filter feeders and as such they need to be depurated according to the Italian regulation of food safety: Reg. (CE) 178/2002, Regg. (CE) 852/2004, 853/2004, and 854/2004 (Federcoopesca, AGCI Agrital, Lega Pesca, 2011). Other relevant regulations are Reg. (CE) 2073/2005, d.lgs. 193/2007.

There are three categories of areas where molluscs are farmed or caught: A, B and C. Molluscs caught in area A do not require depuration since under category "A" fall offshore areas where there is very low risk of contamination. Molluscs produced in area B must be depurated according to Italian regulation, while molluscs of area C are deemed not safe for human consumption. They can be however used for harvesting juveniles. The Chioggia farm where the oysters will be grown falls under area B and, therefore, the model includes a depuration stage (Regione Veneto, s.d.). In order to better describe the process, I visited the local CDM together with the veterinarian Dr Boffo and my assistant supervisor, Dr Bertolini, PhD. The visit is fully described in the next section.

3.1.6 Depuration and packaging

Once they are transported to the CDM (Mollusc Depuration Centre) and unloaded, oysters will be weighted and assigned a reference number – this ensures product traceability. Then, they will be put into large tanks and clean and depurated seawater is continuously poured over them from shower heads on the ceiling. Water is continuously cleaned and circulated to ensure oxygenation and proper depuration. During their

[5] See also chapter Results below.

whole stay, molluscs are kept in different refrigerating rooms, which are used to keep separate products at distinct stages of depuration.

During depuration, water passes through sand and bio-filters, then after depuration through a skimmer and UV-light filters. The system is semi-closed, so water has to be taken in from the sea regularly. The initial water input passes through a first det of filters and refrigerated to maximize the depuration potential of molluscs.

After an 8-12h stay in the depuration section, oysters will be moved to the selection area. Here they are weighted and selected for market. In the case of oysters, these operations will be performed manually. Presently, no proper machinery for calibre-selection of oysters exists at the Chioggia molluscs depuration centre. Selection will be done manually due to the relevance consumers place on oysters' appearance.

During this stage, oysters will also be packaged, their boxes piled on pallets, and wrapped in nylon for later shipping. The oysters will be packaged in wooden cassettes with straw lining, closed with plastic strips. The plastic strips could be replaced by a more sustainable form of packaging – e.g., bioplastics, other materials – once the production chain exist.

Inside their cassettes, oysters are placed in groups of twelve with the concave side facing down. This is to preserve the water that they have inside. This is a crucial feature for final consumers and testifies the freshness of the product.

3.2 Visiting the depuration plant in Chioggia

In March 2022, I visited the depuration plant for mollusc located in Chioggia together with my assistant supervisor, Dr Bertolini, PhD, and the veterinarian of the mussels' farm that will host the oyster farm. The main goal was to learn about the procedure and fine tune the modelled production chain.

3.2.1 Molluscs arrive at the plant[6]

All farmed and fished molluscs in the area are brought to the CDM. The dock is divided, and one side is dedicated only to smooth clams, *Callista chione* or *fasolari* in Italian. Currently, the oyster farm located in Veneto that provided the information I used in this work is not served by this plant. Therefore, no oysters are currently treated by the Chioggia plant.

The required cleaning and depuration level is dependent on the farming or fishing location – as prescribed by law. Additionally, the cleaning procedure that the farmers adopt on their boats influence the level of cleaning needed as well.

All molluscs come with a transport document[7] and a registration document[8]. They are both produced by the anglers or farmers at harvest and contain information needed for traceability, among which are the name of the fishing or farming company, geographical origin, quantity, sanitary status, and destination.

Molluscs are weighted when caught, but they are weighted a second time at the CDM. This second weighting is the official one that will be reported on the official documents. During their transportation, molluscs can

[6] All following information was gathered directly during the visit.
[7] *bolla di trasporto* (DDT)
[8] *documento di registrazione* (DDR)

lose some of their weight due to water expulsion. After the weighing, the batches are officially taken in by the CDM and assigned an official registration number. This is also required for traceability purposes.

Usually, molluscs lose a part of their weight during processing as well, but the percentages vary depending on the species. For example, smooth clams have almost no weight losses, while mussels can lose up to 12% of their initial weight due to water losses, and up to 30% of their overall weight during the entire production processes. Oysters are likely to have a weight loss comparable to the smooth clams' one, due to the fact that they are farmed distanced from one another.

3.2.2 Depuration

The depuration process works as follows. First, water is taken in from the lagoon and depurated. The water is circulated through a mechanical filter and then left to sediment. Here, water is separated from heavier substances. Then, water is chilled and circulated through UV-light filters before passing to the actual depuration part of the plant.

The system found at the Chioggia CDM is a semi-closed one. Therefore, water is taken in when losses occur, usually when molluscs are transferred from the depuration to the selection section. Full exchange of water occurs over a period of 10 days. The semi-closed structure allows temperature control: in fact, molluscs filter the fastest and most efficiently around 15°C. The optimal range of temperature goes from 12°C (wintertime) to 17°C (summertime). However, the crucial aspect is to not subject animals to abrupt temperature changes.

Molluscs are placed in plastic containers called *bins*, showed in *Figure 13*. They are depuration tanks with two different bottoms. The first bottom is placed 10 to 15 cm from the real tank bottom and is full of holes. This ensures separation of the molluscs from the materials expelled during the depuration process, which deposit onto the bin bottom. Bins can be placed one on top of the other and each can contain 250 to 300kg of product.

All bins have a pipe inside them that collects water above the bottom covered with holes. The pipe conveys the water to bins placed below or to the wastewater collection system that then moves it to further depuration. This ensures that all the animals in the pile of bins receive clean water and can operate the filtration process. The water that arrives to lower tanks can be kept clean and free of contaminants, since it is taken above the expelled materials, and still rich of oxygen so that the animals can breathe. Oxygen content of the water is monitored throughout the depuration process.

Figure 13 - Example of plastic bin for mollusc depuration from the producer's website

The filtrated and chilled water continuously falls on top of the bins from shower heads placed on the ceiling. It flows through the piles of bins and then goes into another filtration and depuration process to separate it from any organic matter and contaminants.

The water used for molluscs' depuration is collected and transferred to another depuration process. First, it is circulated through a set of tanks with sand and bio-filters that eliminate nitrogen compounds such as ammonia. Then, the water passes to a depuration room that contains a skimmer to remove any foam of organic origin, a chiller to adjust water temperature, and another set of UV lights to eliminate viruses and bacteria (*Figure 14*).

Molluscs are kept in the bins for depuration for 8 to 12 hours, depending on their origin and the local meteorological conditions. In fact, farmed or caught animals need different treatments. The weather can also influence their contamination levels. Heavy rains and storm surges positively affect the depuration time. Furthermore, depuration periods are calculated based on historical data relative to the geographical area: 8 hours have been proved effective for animals farmed inside the lagoon under normal weather conditions, while 12 hours are sufficient in the case of heavy rain.

Water is continuously monitored to verify proper levels of oxygen, pH, salinity (heavily rain-dependent), and inorganic nitrogen compounds.

Figure 14 - Picture from the visit to the depuration plant. In the picture, a skimmer.

3.2.3 Selection and packaging

After the depuration process, and if required by the production chain, the depurated products are transferred to the selection and packaging area of the plant. In this area animals are divided by category, weighted, and packaged for shipping. Depending on the full value chain, molluscs can be shipped to retailers, restaurants, or shops. Smooth clams, for example, are packaged on board of fishermen's ships, not at the CDM. The CDM serves as warehouse and logistic centre from which the smooth clams are shipped to other selection centres that package them into consumer-sized batches.

In the existing selection chains, clams and mussels are moved from the depuration area to the selection area still in their bins. The bins are then emptied into a tank that channels the product onto a conveyor belt (*Figure 15*). This leads to a machinery that automatically divides molluscs based on their weight and dimension. The process is automated for both mussels and clams, but is going to be manual for oysters, given that no machinery for oysters is currently present at the plant.

Figure 15 - Conveyor belt for mussels in the Chioggia depuration plant, photo from the visit.

While the product is on the conveyor belt, workers inspect the animals to check that shells are intact, that no shell is empty, or that no dead animal is packaged into the batches along with the rest. Then, animals end in a machinery that weighs and divides the product according to weight (*Figure 16*). Finally, molluscs are packaged according to their category. During this phase, oysters will be assigned a calibre by the workers and divided for packaging accordingly.

Figure 16 - Photo from the visit. The machine that automatically separates and weighs the molluscs.

There is an optional additional filtration procedure – lasting around 4 hours – that the animals can be subjected to. This happens in the case further cleaning is needed. For example, clams can still contain sand, and this has to be taken out before final shipment. There is another situation that may require further filtration. When expiration date is approaching, yet the animal is still alive, molluscs can be immerged to increase their shelf life. In fact, the expiration date is calculated starting from when they are removed from water at the end of the depuration process. This practice is perfectly healthy since the animals are alive the entire time and can contribute to avoiding food waste.

When bins are moved to the selection area and emptied, along is emptied the water. This final wastewater is not depurated again but filtrated before discharge in the lagoon. This final filtration step ensures that only safe water is discharged into the environment. While water is filtrated and tested, the waste material contained by the bins is collected and gathered. This material is then disposed separately and cannot be discharged into the lagoon.

During the entire process, production waste – such as dead shells and animals – are collected to serve as input into other production chains, such as fertilizer or feed.

Chapter 4: Results

4.1 Goal and scope definition

The scope of this work is to assess the potential environmental impacts of a new oyster-based product farmed in the Lagoon of Venice, near Chioggia. The plant and production process modelled are the ones described in the section above. The present assessment could serve as basis for further assessments once the system is actually created, and for an estimate of the costs associated with production and final price to customers. The intended audience for this work includes those who will set up the farming plant, as well as Dr Bertolini as lead of the research project MAREA. Additionally, this work could be of interest both as an LCA study and as an aquaculture modelling exercise.

The modelled system is a steady-state system, where production is mature, and the set-up years are ignored. The product under research is oyster of the species *Ostrea edulis*, which will be farmed near Chioggia in a joint mussel and oyster system. The farm is a small-scale one, operated at the local level. Final product is likely to be sold in the Veneto region, specifically in the larger metropolitan area of Venice. However, due to the immaturity of the production chain, it is not possible at this time to define an actual market of reference. Still, the production is likely to stimulate local demand for oysters.

A procedural decision under the Life Cycle Inventory modelling was to take the inputs from a "unit" dataset. As described above, these kinds of datasets are more comprehensive and can be connected with other production processed more easily.

This work assesses impacts using the ReCiPe 2016 methodology. There is no consensus in literature over which impact categories are better suited to describe the environmental impacts of aquaculture (Jennifer S. Ford, 2012) (Johan Andrés Vélez-Henao, 2021) (Nathan L. Pelletier, 2007) (Patrik J. G. Henriksson, 2012). However, a number of studies has used the same impact categories to assess aquaculture's impacts. The most commonly used are: climate change, acidification, eutrophication, as well as cumulative primary fossil energy demand (Patrik J. G. Henriksson, 2012). I then chose to also include some of the indicators used in the other LCA-based study on oyster farming it Italy (E. Tamburini, 2019). Therefore, my results include ozone layer depletion potential and marine ecotoxicity.

At first, all the overall results for all impact categories included in the ReCiPe 2016 method were considered. Full results are reported in *Annex 2*. The overall impacts of each stage of the value chain within the boundaries of the system, as well as impacts of the total process are considered at first, then the share of contribution of different production stages concerning three main indicators: global warming, terrestrial acidification, and marine eutrophication. The discussion, however, focuses on the impact categories most reported in the literature.

For this project, I chose as functional unit 1kg of oysters at oyster gate. The unit is relative to one year of output and, as such, ignores the initial set-up periods. I scaled all the inputs in the inventory considering the weight of oysters that will likely be produced in one year at the Chioggia farm.

I opted for mass allocation even though price allocation is also frequently used (Fulvio Cellura, 2011). I decided for this method for three main reasons: first of all, the ISO standard recommends leaving price allocation as last resort, since prices fluctuate over time (ISO, ISO 14040, 2006).

To define the system boundary, the first step was the development of the production chain. As such, the project started with the modelling of the production chain, the literature review, and the visit to the CDM (Depuration Centre for Molluscs) in Chioggia. The results of this process have been described in the sections above. The system is cradle-to-gate, so manufacture of inputs is considered wherever possible, while shipping to customers or retailers and all that happens after selection and packaging is excluded *(Figure 17)*.

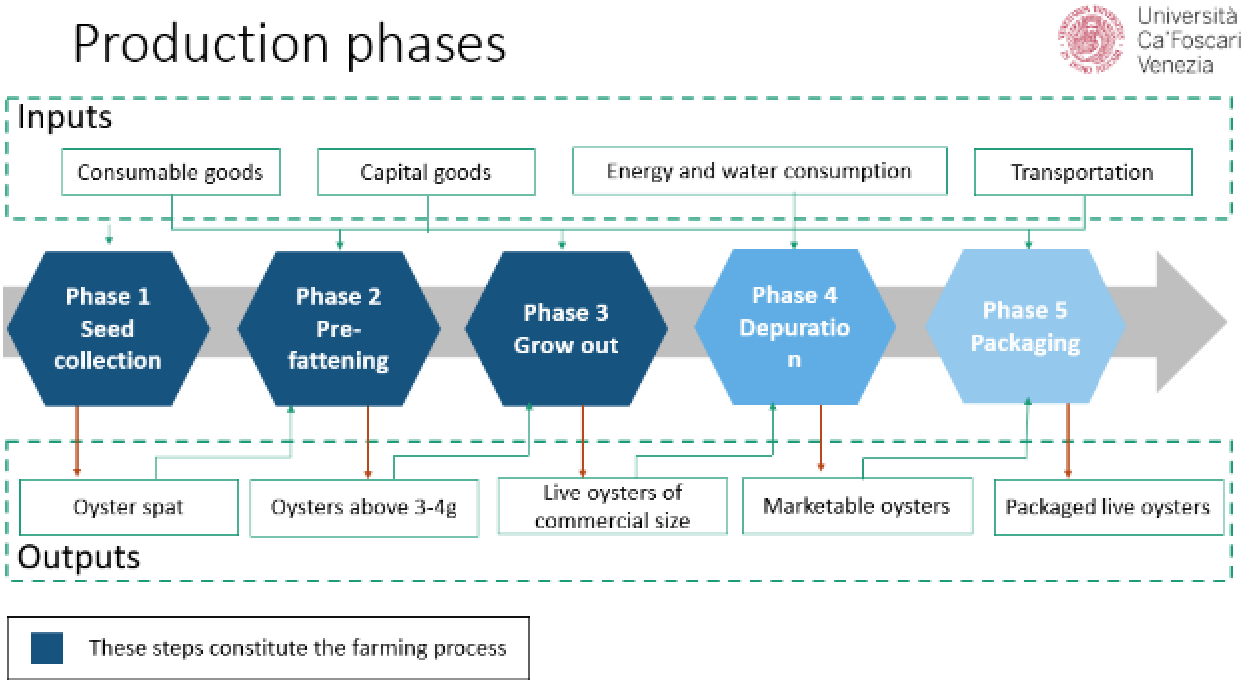


Figure 17 - System boundary of the project

The main outcomes of this project are the inventory produced during the analysis, the graphs resulting from the impact assessment, the graph of the system boundary and this final report.

Privileged sources of data were always direct ones. As such, information coming from Dr Boffo was always preferred regarding the production chain and depuration plant, and information from Mali Ston was privileged for the production chain. Finally, fishmongers located near the author's town were engaged and a kilogram of oysters was sourced directly to calculated direct dimensions and weight of packaging. The work is also based on literature review and on the databases present in the software for background data. In fact, this work was done with SimaPro PhD, version 9.0.0.49, and employed ecoinvent 3, cut-off by classification, unit and agrifootprint.

As described above, mass allocation of impacts was chosen. Allocation is also used in the model in its original sense, namely allocation between co-outputs of a single production process. In fact, as mentioned elsewhere in this work, the Chioggia plant will farm both oysters and mussels. For the weight proportion, first an estimate of final output of the farm was conducted together with Dr Boffo and based on information from another farming facility in Veneto. In one year, the mussels' production of the Chioggia plant is of approximately 100 tons – all precise figures are in *Annex 1*. The yearly oyster production is likely to be 20-25% of the mussels' production. The lower estimate was used to account for underestimated losses and to express the highest environmental impacts possible. Therefore, the final estimate of oyster production in one year is 20160 kg. The final mass allocation quotient is 0,2.

Moreover, another allocation procedure was required for the depuration process. In fact, the depuration centre CDM treats a variety of mollusc over the course of one year. The weight allocation criteria was used for consistency and the allocation factor was calculated based on the mass treated by the plant in one year. This way, the second allocation criterion (only for depuration) is 0,04.

A final note on the system boundary is that the dock from where anglers sail is very close to the farm, therefore round trips are short and need very little fuel.

4.2 Life Cycle Inventory

After the definition of the system boundary, all the inputs required in the production of oysters were listed (*Table 2*), based on information from Dr Boffo, the other oyster farm in Veneto, and from the Mali Ston project. As customary in LCA procedures (EU Joint Research Centre, 2010), the inventory was continuously updated throughout the project to reflect added information, modifications to the system and literature review.

The full set of inputs is divided into inputs required in the actual yearly production, materials that build the farming facility, and machinery and inputs required in the depuration and packaging process.

Production phase	**Input**	**Unit of measure**
Farming	Sea occupation	m^2
Depuration	Seawater	l
Farming	Boat hull	kg
Farming	Electricity generator	amount
Farming	Boat motor	amount
Farming	Natural gas	m^3
Farming	Gasoline	L
Farming	Motor oil	kg
Farming	Steel ropes	kg
Farming	Wooden poles	kg
Farming	PVC technical gear	kg
Depuration	Electricity consumption	kWh
Depuration	Skimmer	amount
Depuration	UV light filters	amount
Depuration	Sand bio filters	amount
Depuration	Mechanical filter	amount
Depuration	Bins	amount
Depuration	Chiller	amount
Packaging	Labels	kg
Packaging	Pallets	amount
Depuration	Scale	amount
Farming	Bricks	kg
Farming	Coupelle collectors	kg
Farming	Rebar	kg
Farming	PP ropes	kg
Farming	Lantern nets	kg
Farming	Cement	kg
Packaging	Cassettes	kg

Packaging	Straw for lining	kg

Table 2 - Inputs used in the production chain

The absolute quantities for each input were taken preferably from direct data, even though the farming system or the species were different from that of my project. Therefore, I tried to collect as much information as possible from the other Venetian farm and from the Mali Ston project. When not possible, estimates were used.

The first step in the creation of the inventory was to create an Excel spreadsheet to keep track of all the information and to allocate all inputs in reference to the life service, the allocation quotient, the farming stage, and the final output quantity. The full file is reported into *Annex 1*.

In total, I found twenty-nine inputs for the production of 1kg of oysters at farm gate. Obtaining the information was challenging, since production is not active yet, and some approximations had to be made.

4.2.1 Input calculation

All final input quantities, scaled down by allocation and service life, and reported against the functional unit are listed in *Table 3*. All units are referred to years since they were scaled against the service life and are thus relative to 1 year of production. Furthermore, all inputs employed in the farming process have been scaled according to a periodization factor, which represents the share of time the input is allocated to. To clarify, oysters are farmed for around 2,5 years. Of this period, seed collection lasts 6 months, pre-fattening 10,5 months and grow out 12 months. The infrastructure was allocated also regarding time required for each stage, to assess impacts about each stage in the evaluation stage.

In the next paragraphs are reported all the inputs as well as the procedure conducted to include them in the SimaPro assessment. Geographic origin of the input is indicated by an acronym. RER means rest of Europe, ROW rest of the world, GLO global. Whenever possible, geographical location was selected after the most likely origin of manufactured goods. This is, again, an estimate which could be improved once the system is operational, and farmers can keep track of actual origin of materials used in production.

Production stage	Input	Entry	Unit of measure
1. seed collection	Boat hull	**0,0000355054**	kg/y
1. seed collection	Boat motor	**0,00000025361**	
1. seed collection	Bricks	**0,002048611**	kg/y
1. seed collection	Coupelle collectors	**0,000383135**	kg/y
1. seed collection	Gasoline	**0,000932018**	L/y
1. seed collection	Motor oil	**0,0000014646**	kg/y
1. seed collection	PVC technical gear	**0,0000181078**	kg/y
1. seed collection	Rebar	**0,001181101**	kg/y
1. seed collection	PP ropes	**0,000313542**	kg/y
2. pre-fattening	Boat hull	**0,0000621345**	kg/y
2. pre-fattening	Boat motor	**0,000000443818**	amount/y
2. pre-fattening	Natural gas	**0,001655029**	m^3/y
2. pre-fattening	Gasoline	**0,001631031**	L/y
2. pre-fattening	Electricity generator	**0,000000155336**	amount/y
2. pre-fattening	Motor oil	**0,00001293955**	kg/y
2. pre-fattening	PVC technical gear	**0,0000316886**	kg/y
2. pre-fattening	Sea occupation	**0,001414492**	m^2/y

2. pre-fattening	Steel ropes	**0,000352251**	kg/y
2. pre-fattening	Wooden poles	**0,033721415**	kg/y
2. pre-fattening	PP ropes	**0,005070139**	kg/y
2. pre-fattening	Lantern nets	**0,020689405**	kg/y
3. grow out	Boat hull	**0,0000710109**	kg/y
3. grow out	Boat motor	**0,00000050722**	amount/y
3. grow out	Natural gas	**0,001891461**	m^3/y
3. grow out	Gasoline	**0,001864035**	L/y
3. grow out	Electricity generator	**0,000000177527**	amount/y
3. grow out	Motor oil	**0,000014788**	kg/y
3. grow out	PVC technical gear	**0,0000362155**	kg/y
3. grow out	Sea occupation	**0,001616562**	m^2/y
3. grow out	Steel ropes	**0,000402573**	kg/y
3. grow out	Wooden poles	**0,03853876**	kg/y
3. grow out	PP ropes	**0,016955556**	kg/y
3. grow out	Cement	**0,276816468**	kg/y
4. depuration	Seawater	**2,172619048**	L/y
4. depuration	Electricity consumption	**0,218253968**	kWh/y
4. depuration	Skimmer	**0,000000396825**	amount/y
4. depuration	UV light filters	**0,000000396825**	amount/y
4. depuration	Sand bio filters	**0,00000238095**	amount/y
4. depuration	Mechanical filter	**0,000000396825**	amount/y
4. depuration	Bins	**0,00000166667**	amount/y
4. depuration	Chiller	**0,00000015873**	amount/y
4. depuration	Scale	**0,0000000793651**	amount/y
5. packaging	Pallets	**0,003174603**	amount/y
5. packaging	Labels	**0,000980357**	kg/y
5. packaging	Cassettes	**0,490196078**	kg/y
5. packaging	Straw for lining	**0,323517857**	kg/y

Table 3 - Inputs referred to the functional unit

4.2.2 Inputs from stages 1 to 3

Information on sea occupation extent was given by the Chioggia plant and is of 9106 m². It is a small farm located in the Lagoon. The occupation was estimated for 20 years, even though it is likely that the occupation will last longer than 20 years. However, the dimension and the timespan are long enough that this input has a minor impact in the final analysis. In SimaPro, I picked the input under nature, "*occupation, sea and ocean*" with an amount of one measured in m²a – square metres per year. As imagined, after calculations, the final value is quite low.

Spat is not considered as an input by SimaPro. Based on the estimated survival rate and the final quantity of output, I estimated the necessary quantity. This was not necessary for the scope of the work but could prove interesting during the actual production phase.

Regarding the boat used by the plant, my first assumption was that farmers would not buy a different boat and work with the one they already have. This is because setting up a new production line will be expensive, and I assumed that other ancillary costs will be kept to a minimum. Furthermore, a boat hull can last decades. Next, I split the boat into hull and motor since they have different durations. The hull is made of glass fibre and can last up to 50 years, while the motor has a lifespan of about 7 years. They make up two different voices into the inventory. The allocation factor is, however, similar for both and is 0,2. Both are also allocated with respect to the use in different farming stages.

The farm was not able to provide precise information on the motor's model, only the relative brand. After research, I could not match the motor to a model and thus report the actual product into SimaPro. I, then, used an approximation. I input under technosphere "*marine electric motor {GLO}| marine electric motor construction | Cut-off, U*". The default unit of measure is in amounts.

The boat hull is in glass fibre. A model number for the boat was available and it was, thus, possible to retrieve a technical description. After obtaining the composition and total weight, I was able to account for a more precise input in SimaPro, "*glass fibre {RER}| production | Cut-off, U*". In this case, I picked RER for the geographic origin because the boat is from a European manufacturer. The unit amount in this case is of 1kg.

The production plant hosts an electricity generator powered with natural gas. No information on the precise type of electricity generator was provided. The final assumption was to consider a standard gas motor in lieu of an actual electricity generator. Although the scaling and allocation procedure was easy enough to conduct, considering a service life of 20 years and an allocation factor for oyster-mussels of 0,2. Research within the employed databases in SimaPro yielded no satisfactory results, so I was unable to input it precisely. However, the final value reported to the functional unit is small, so I assumed it would not make a significant impact on the final assessment. In SimaPro, the input was from technosphere and materials, "*gas motor, 206kW {RER}| production | Cut-off, U*". The default unit of measure was in units.

Instead, I could get from the farm quite detailed information on natural gas consumption. The generator uses approximately 350 kg of gas over the course of one year. By using the density of natural gas[9], I calculated the final volume employed over the course of one year by the farm. This was useful because the input on SimaPro was expressed in volume. The input from technosphere was "*natural gas, from medium pressure network (0.1-1 bar), at service station {RER}| processing | Cut-off, U*".

The information regarding the boat's fuel consumption was relative to amount required for a single round trip. The boat uses gasoline, specifically 3,5 litres to conduct the short round trip back and forth from the plant. I managed to obtain information regarding the number of total round trips that are conducted at this moment in one year. I assumed no to minor variation of this number, since the trips are done to check on the mussels. My assumption is that, for convenience and routine, the farmers will make use of the same trips to check on the oysters as well. This is likely at least for the seed collection step since juveniles of both oysters and mussels spawn in the same period. Further corrections could be done once the system is operational, with real-time data. Overall, farmers do 150 round trips in one year, each using 3,5L of gasoline. In one year, the boat consumes 525L of gasoline. I converted this measure into weight with the density[10] to obtain a total of 357kg of gasoline. The final value for this input is quite low, a fact which can be explained by the close geographic proximity.

Both the boat motor and the electricity generator use motor oil. No information on the kind and composition of the motor oil was received. Therefore, calculations assume that both engines would use the same kind. This is not necessarily true, and further assessment could take note of this fact. The boat uses 1L of oil in 1 year. The engine of the generator has a 5-chilogram tank, and the oil is fully changed over 1,5 years. Overall, in 1 year the production facility will go through 4,16kg of oil. To reach this estimate, I used motor oil average density of 825 kg/ m^3, since I did not have the brand nor the product code for the specific type of oil.

I then moved onto the actual constituents of the farm. The first one is steel ropes. The information received from the farm were detailed but provided in a hardly convenient fashion. My starting information were the

[9] Natural gas density: 0,657kg/m^3
[10] Gasoline density: 0,68kg/L

diameter of the ropes, and the length and number employed in each of the two sections of the farm. The older section has seven 8mm-wide steel ropes that are 441m long. Based on this, I calculated the volume of each rope, its mass by using the density of 7850 kg/m³, and then the total mass. I followed an analogous process for the newer section of the plant, which has 20 133m-long ropes. By summing partial results, I obtained the final total mass, which I then scaled against a service life of 20 years, the allocation factor, the allocation according to farming stage, and finally the functional unit. In Simapro, I input "*Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8 | Cut-off, U*" from technosphere, with unit amount of 1kg.

A similar calculation procedure was adopted for the wooden poles. Traditionally, chestnut is employed for this purpose, and poles last for around 20 years, if not more. The information at my disposal was the diameter of each pole, and its length. I calculated their volume and reached an estimate of weight using the density[11]. In total, the plant has 366 wooden poles, so I easily got an estimate for the total weight, which was scaled again against the service life, the allocation factor of 0,2 the allocation according to farming stage, and the functional unit. Simapro had a wide array of inputs for wood. My best estimate was "*Sawnwood, hardwood, raw {RoW}| sawing, hardwood | Cut-off, U*", with unit amount 6,67 E-4 m³, since the unit of measure of this input was by default m³.

Polypropylene ropes are used in all farming stages: collectors are tied together and hung with ropes, lanterns are hung with ropes, and in the final farming stage, oysters are glued in pairs to ropes. To account for amount required under each stage, I started with the type of rope employed. Information from the MAREA project as well as from the Mali Ston farms was used. The final product is a PP rope with length 15 m and diameter 10 mm. Each group of collectors employ half the length – and approximately the weight – of one rope. I assumed each lantern would use one rope. I also assumed each rope would be filled as much as possible with oysters. Accounting for a 10 cm distance between oysters – the same distance left by Croatian farmers in between – and 3 metres of useful length – considering water depth of around 6-8 m at the farm – each rope could host possibly up to 80 oysters. These estimates are likely to be corrected once the system is operational but were useful approximations in the process. All of the calculations above ended up in estimates of quantity for ropes in each stage. In SimaPro, both material input and manufacture were accounted for. The material was input as "*polyethylene, high density, granulate {RoW}| production | Cut-off, U*", under plastics, thermoplastic, with a unit amount of 1kg. The assumption is production would not occur in Europe. Manufacture was accounted for as "*weaving, bast fibre {RoW}| processing | Cut-off, U*", unit amount of 1kg.

Regarding the production process, the first input considered was PVC gear for personnel. Since the production plant did not provide detailed information about this, gear for anglers was researched and two different products found: a pair of oilskin pants and a set of waterproof boots. Both sources indicated the weight of each garment. The farm employs three anglers, so the gear was accounted for three employees. Considering the harsh weather conditions that the garments would find themselves into, service life was estimated to be 1 year. Allocation was then performed according to the mass factor 0,2 (oyster mass over total) and the periodization coefficient (farming stage). In SimaPro, the materials were input as "*polyvinylidenchloride, granulate {RoW}| production | Cut-off, U*", with amount unit 1kg. This is not necessarily the best input of choice, but simply an estimate. Further work could also contact producers to get a better sense of how the garments are produced and define a better input. However, the final value is quite low and the impact on the final results is small.

The other materials for production are: coupelle collectors, rebars, bricks, lantern nets and cement.

[11] Wood density: 590 kg/m³

Coupelle collectors are required for seed collection. Despite research, I was unable to find the actual plastic material composition. Therefore, I estimated it to be high-density polyethylene (HDPE). The weight of a single collector is around 20g. In order to calculate the required number of collectors, the first step was to calculate the projected number of oysters collected. Starting with the estimated output in weight, the next step was to estimate the number of oysters produced by the plant at the end of the farming period. Estimating an average weight of 85 g (the average of the most widely sold *Ostrea edulis* calibre, ranging from 80 to 90g[12]), the number of oysters resulted to be 237,176. Survival rate for each production stage were provided by real-time data from Mali Ston farms. In small-scale farms, survival rate of each stage is of around 85%. Going backwards, next estimates were the number of oysters before the grow out stage, before the second lantern stage and at the end of the collection period. In the end, the estimated number of oysters caught in seed collection is of 386,202 individuals. This estimate could be updated once the production process eventually begins with real-time data.

The number of oysters that can be caught by each collector was provided by the Croatian farm and is of approximately two hundred per collector, with fluctuations – even significant ones – from one year to the next one. The actual collection rate can be adjusted with real-time data once the farm becomes operational. Using this number, the total number of collectors required to collect 386,202 individuals is 1931. Considering a unit weight of 20g, total estimated weight is of 38,62 kg. In SimaPro, the input is "*Injection moulding {RoW}| processing | Cut-off, U*", with unit amount of 1,006kg. This value comes from the fact that, under the input description, it is stated that 1kg of plastic feedstock yields 0,994kg output. Therefore, a proportion was used to calculate the quantity needed to yield 1kg of output.

Collectors are bundled together by a rebar, tied with rope and placed underwater with bricks that serve as weight. Groups of fifteen collectors use two bricks each and form a station. Collectors in Croatia are hung from the longlines, but the modelled scenario in this instance mimics seed collection performed in the context of the MAREA project. Further work could modify this assumption if the real-life production uses a different technique. With the estimated number of collectors, the stations will be 129. Of course, this is a very high number. Probably, stations will hold a larger number of collectors once the system is operational, but at present this is the best estimate possible. Accounting for two bricks per station, total weight of bricks is of 826 kg. This was scaled against the service life (20 years) and allocation ratio 0,2. In SimaPro, the input of choice was "*clay brick {RER}| production | Cut-off, U*", with unit amount of 1kg.

The Croatian farms provided information regarding dimensions of the rebar (diameter and length). To calculate the weight, after obtaining the volume of one rebar, the density of low-carbon steel was used[13]. Considering the estimated number of collectors and the fact that a rebar is used for 5 collectors, the estimated number of rebars is 386 and weight is 238,11 kg. The final value was scaled down to a service life of 5 years and the allocation factor. Both bricks and rebars will only be used during seed collection for oysters, so both weight and periodization allocations were performed against a unitary factor. The input in this regard is "*steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Cut-off, U*", unit 1kg.

Considering the modelled production chain, two sets of lantern nets will be employed in the production chain: a small-links one and one with larger links, considering different growth of oysters in between production phases. Weight for both types of lantern nets was researched. After no significant results, the weight estimate used comes from a producer met by my co-supervisor, Dr Bertolini, at an internationally significant aquaculture faire[14]. Unitary weight of nets is of 2 kg. To estimate the number of nets required in

[12] Oysters of *Ostrea edulis* can be sold from 20g (calibre 6) to 110g (calibre 000), but the most widely sold is calibre 0 (80-90g). The assumption was that, on average, oysters would weight around the 80-90g category. This would account for both larger and smaller oyster, with the underlying assumption that most oysters would be bigger than calibre six.
[13] Density: 7850kg/ m^3
[14] Aquafarm: https://www.aquafarm.show/

the first pre-fattening stage, the starting point was the number of oysters survived after collection, 386,202. Estimates from Mali Ston suggest that each floor of the nets hosts about 200 small oysters, with 5 floors available. Total number of lanterns required for the first step is 386, with a weight of about 772 kg. A similar calculation was performed for the second set of nets required. In this case, the unitary weight estimate is the same, but each floor hosts around 100 oysters. The number of floors is analogous. The lantern required for this stage add up to around 1313 kg. Material of production is high-density polyethylene. In SimaPro, the input was "*polyethylene, high density, granulate {RoW}| production | Cut-off, U*", with unit amount 1kg. Further information by actual suppliers for the value chain would be helpful in better estimating this input.

The final material input required in the farming process was cement, used to glue pairs of oysters to the rope for the final grow out stage. The Mali Ston project provided the amount of cement used for 10,000 oysters, which is of 20 kg. To calculate the full quantity needed, I used the estimated number of oysters after the lantern pre-fattening stage, 279,031 to obtain the final weight needed. Naturally, once the system is operational, this information can be validated and adjusted if necessary. In SimaPro, the input chosen was materials, construction, concrete: "*concrete, normal {RoW}| unreinforced concrete production, with cement CEM II/A | Cut-off, U*". The default unit of measure in SimaPro was m^3, so I converted a unitary weight into volume using concrete density. The unit amount was then 4,16E-4 m^3.

4.2.3 Inputs from stages 4-5

This marks the end of the input necessary in the farming process. The next inputs considered are required for the depuration stage. Only a couple of materials are actually described and listed in the following paragraphs. This is due to the fact that it was not possible to obtain enough information on the machinery to account for their composition in SimaPro. The farming plant did not have information regarding weight or composition of the machinery, while the manufacturer did not wish to disclose sensitive information. As such, the analysis was conducted only regarding the equipment on which information was available in SimaPro's databases or for gross approximations.

Furthermore, a new allocation coefficient had to be calculated. Since the depuration plant in Chioggia processes 3 types of molluscs presently, four considering the oysters, the new coefficient was calculated taking into consideration this fact. Regarding the choice of the allocation method, mass allocation was chosen again. The considerations behind this choice are the same mentioned above regarding the farming allocation mass coefficient: prices would fluctuate too much and not be reliable. The allocation coefficient for the depuration stage is 0,04.

The machinery used by the depuration plant is the same that was listed in the section on the modelled production process: a chiller, a mechanical filter, a series of sand bio-filters, a skimmer, a scale, UV lights (one UV light filter) and a number of bins.

The only machinery found in SimaPro was the UV light filter. As such, the chosen input was from the category materials, construction, others: "*ultraviolet lamp {GLO}| ultraviolet lamp production, for water disinfection | Cut-off, U*". The default unit of measure is in units; therefore, the final input is of 1 unit. No information was received on the total numbers of UV lights.

It was possible to input the bins after research on the manufacturer's website. The weight of one bin is of 73 kg. No information, however, was provided on the number of bins available at the depuration centre, nor the number of bins used over the course of one year. No elements were available to make an estimate, so the final input was of a unitary bin, with the hope that further assessment could benefit from more complete information. The SimaPro category was "injection moulding {RoW}| processing | Cut-off, U". The default measure was weight. Since the idea was to consider the bin input as a unit, the input value was of 73 kg.

The two other information to be considered were the electricity consumption and the seawater use over the course of one year.

Seawater is considered only in the form of water employed by the depuration system. Considering that the system exchanges fully the water over the course of 10 days, this was the starting point of the calculation. Over the course of one year, the depuration plant employs approximately 1.000.000 litres of water from the lagoon. This quantity was scaled against the functional unit and the allocation factor relative to the depuration plant. To input this in SimaPro, the category of choice was "*water, salt, ocean*" under nature. The unit amount is of 1 m^3.

The electricity consumption was provided by the plant and accounts to 110,000 kWh. This amount was scaled against the allocation coefficient and then input in SimaPro as "*electricity, medium voltage {IT}| electricity voltage transformation from high to medium voltage | Cut-off, U*". Medium voltage was chosen because it is usually used in industrial processes. The unit amount was 1 kWh.

For the packaging, inputs to consider are: cassettes, labels, pallets, and straw. Packaging was considered in its essential components since a precise description of the packaging which will be used was not available. The starting point was to consider a packaging analogous to that of other oyster products on the market.

To input for the cassettes, a cassette of oysters from a generic producer was purchased. The cassette was measured, and its weight and number of oysters inside recorded. The form of the cassette was, however, different from the kind most commonly found on retailers' websites. In fact, usually products available come in a sort of small chest with a lid. To correct for this, the weight was doubled. The approximate estimate is of 0,5 kg per cassette. Accounting for the estimated number of oysters at the end of the farming process, 237,176, the total weight of cassettes was calculated. No losses in the depuration stage are assumed since losses would likely be comparable with those of smooth clams[15]. Input in SimaPro was "g*lued laminated timber, for indoor use {RER}| production | Cut-off, U*", with a unit of 6,67E-4 m^3 after conversion.

The number of labels was estimated to be the same of the cassettes, considering that each cassette would have its own label. The material of which the labels will be made is likely to be polypropylene (PP). Considering 1g per label, the final weight of 19.8 kg was input in SimaPro as "*Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, U*", with unit of 1,025kg. This quantity was calculated considering that the input description stated that 1 kg of the process yields 0.976 kg of extruded plastic film. A proportion was used to calculate the unitary input.

To estimate the quantity of straw necessary, the dimensions of the purchased cassette were used to calculate an approximation of the volume. Assuming that straw would fill half of the volume, an estimate of the amount of straw needed was calculated. Unfortunately, the purchased cassette did not have any straw inside to validate this measure. Actual employed quantities could be input once the production process is online. The input in SimaPro was "*wheat straw, at farm/IT Mass*" with a unit of 1 kg.

Finally, the last input was the pallets. Information on the number of pallets used in one year by the depuration and shipping facility was known. The total 1600 pallets were input in SimaPro with "*EUR-flat pallet {RER}| production | Cut-off, U*", 1 unit.

[15] After discussion with the veterinarian, Dr Boffo. New information from real-life data could correct this estimate.

4.3 Waste scenario and treatment

Although not a regular step in the LCA procedure, the creation of a waste scenario and treatment is necessary in SimaPro to conduct the analysis (PRé, 2021). The waste scenario tells the system how to consider and evaluate the different end-of-life treatments of materials used in the process under study. The system is quite flexible and allows the consideration of reuse, disassembly, recycle and disposal. The waste scenario of the present work, however, suffers from approximations required since there is few available information on the end-of-life treatment of materials used.

One other caveat is the fact that SimaPro does consider in the waste treatment only inputs expressed in units of mass. Therefore, since part of the inputs of this present work was recorded with different units of measure, not all inputs used have an associated waste treatment. Hopefully this could be addressed when the production chain is operational and more detailed and reliable information is present and accessible.

When describing the end-of-life treatment, a relevant information is the distance travelled by materials. To account for this, the following assumptions were adopted. Whenever possible, the closest facilities were considered. It is not necessarily true that all material will be treated locally. However, since there was no other information available, this assumption serves as basis for the work. Furthermore, usually the worst-case-scenario was chosen. Disposal is usually considered in landfill and incineration is an option. Recycling is considered for material that is not likely to present major fouling or that, in a potential remanufacture process, would disregard presence of fouling. Transportation was considered to happen in Euro5 vehicles, which are vehicles registered since 2009. Trucks' dimension was considered as middle-sized trucks, holding between 3.5 and 7.5 tons of material (Polirecuperi, 2018).

The list of facilities considered, as mentioned just above, is as local as possible. First of all, the closes landfill is located in Sant'Urbano (ISPRA, 2020) , in the province of Padua, 64 km from the Chioggia plant[16]. This landfill is not only closest but among the other short-distanced landfills in the area treats a higher quantity of special waste, which could be materials covered in fouling. Then, the closest incinerator is in Padua (HERA, 2021), located at about 42 km from Chioggia. There is composting plant in the region, in Treviso (Contarina, s.d.), at 87 km distance from Chioggia. Finally, recycling plants considered were: Aliplast (Aliplast, 2022), 66km from Chioggia, and Pintonello foundry (Pintonello, 2021), 55km from Chioggia.

4.3.1 Disposal of inputs – stages 1 to 3

Wooden poles are assumed to be landfilled since they would be covered in fouling. Unit of measure of waste is of 1kg and waste treatment picked was "*waste wood, untreated {GLO}| treatment of waste wood, untreated, open dump, very wet infiltration class (1000mm) | Cut-off, U*". The GLO category was chosen since the only other alternative was relative to Switzerland alone. Transportation was accounted for by selecting: "*transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO6 | Cut-off, U*", with a unitary amount of 64 kgkm.

The steel ropes are accounted for waste under the "steel" material category. The waste treatment is considered to be recycling, with input "*steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U*", unit 1kg. There was no available information on steel recycling in the case of fouling. Most certainly, recycling would not use 100% of material, but there were no other elements to make a better estimate. The transport was considered to be "*transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, U*", with unit amount of 55 kgkm. This is because the closest foundry (Pintonello, 2021) is located at approximately 55 km from Chioggia. Assuming that the

[16] All distances were estimated using Google Maps and rounded to the highest number to account for small variations.

steel would be recycled, then some avoided products were accounted for. These products are material products that are substituted by recycling. In this case, it is "*steel, unalloyed {RoW}| steel production, converter, unalloyed | Cut-off, U*", amount 1kg.

The last element of the farming setup is PP ropes. I considered that around half of the PP could be recycled, picking waste treatment: "*PP (waste treatment) {GLO}| recycling of PP | Cut-off, U*" with amount 0,5 kg. Transportation would be of 0,5kg *66 km = 33 kgkm, under category "*transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U*". The rest of the ropes would end up in landfill, with waste treatment "*municipal solid waste {GLO}| treatment of municipal solid waste, unsanitary landfill, hyperarid infiltration class (-250mm) | Cut-off, U*" 0,5 kg. Transportation was under "*transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U*", with amount of 32 kgkm. In this case, there are two avoided products: "*Polypropylene, granulate {RER}| production | Cut-off, U*", amount 0,5 kg and the electricity required to produce the PP: "*Electricity, medium voltage {Europe without Switzerland} | market group for | Cut-off, U*", amount: 1,13 kWh. This quantity was obtained from description of background process in SimaPro: 0,6kWh for 0,266 kg of input (granulate). Furthermore, I assumed that since recycling could happen in Italy, avoided inputs and electricity would be relative to Italy – or at least Europe.

To account for the end-of-life of the boat, only the hull was considered since the motor was input as a quantity. This is, of course, not desirable. However, there was not any more appropriate information. The hull is made of glass fibre, and I assumed incineration: "*hazardous waste, for incineration {Europe without Switzerland} | treatment of hazardous waste, hazardous waste incineration | Cut-off, U*", with amount 1kg. Transportation was of 42 kgkm, under "*transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO6 | Cut-off, U*".

Motor oil was considered as well with incineration: "*waste mineral oil {Europe without Switzerland} | treatment of waste mineral oil, hazardous waste incineration | Cut-off, U*", with amount of 1kg. Meaning that all waste oil would be burned. The transportation in this case is considered as "*transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RER}| transport, freight, lorry 3.5-7.5 metric ton, EURO5 | Cut-off, U*" with an amount of 42 kgkm.

Rebars used to join together collectors are considered as ferro-metal waste and treated for recycling. The assumptions used are the ones described above, therefore the input of choice was "Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, U", unit 1kg. Transportation is assumed to be to the same foundry where steel ropes are melted and recycled, therefore transportation is of 55 kgkm, under "*Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RER}| Cut-off, U*". Avoided product is similar than in the case of the ropes: "s*teel, unalloyed {RER}| steel production, converter, unalloyed | Cut-off, U*", amount 1kg.

Coupelle would be fully disposed in landfill under waste treatment "*waste polyethylene {GLO}| treatment of waste polyethylene, unsanitary landfill, dry infiltration class (100mm) | Cut-off, U*", amount 1kg. Transportation would be to the landfill in Sant'Urbano, therefore with amount 64 kgkm, under "*transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO6 | Cut-off, U*".

Bricks are inert waste which will be ultimately disposed in landfill. Waste treatment is considered to be "*inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, U*", unit 1kg, while transportation is considered to be to the closest landfill. Transportation is accounted for as "t*ransport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| Cut-off, U*", 64 kgkm.

Nets are considered impossible to recycle since their long stay underwater and presence of fouling. Full disposal by landfilling is considered by "*waste polyethylene {GLO}| treatment of waste polyethylene, open* *dump, dry infiltration class (100mm) | Cut-off, U*", amount 1kg. Transportation is, again, to Sant'Urbano, with transportation of 64 kgkm under "t*ransport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| Cut-off, U*".

The anglers' gear will be landfilled as well, under "w*aste polyvinylchloride {GLO}| treatment of waste polyvinylchloride, open dump, dry infiltration class (100mm) | Cut-off, U*", with amount 1kg. transportation is again of 64 kgkm, under the same transport category.

Finally, cement is the last material input accounted in mass under the farming process. Cement is considered to be inert and, as such, landfilled in a way analogous to that of the aforementioned materials. Waste treatment is "*inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Cut-off, U*", unit 1kg, and transportation is "t*ransport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| Cut-off, U*", of 64 kgkm.

4.3.2 Disposal of inputs – stages 4 and 5

Since it was not possible to input any of the machineries used in the depuration process using their mass, they have not been accounted for in the waste treatment. This is a gross absence, although unavoidable.

Labels are made of PP and considered for recycling. Waste treatment is "*PP (waste treatment) {GLO}| recycling of PP | Cut-off, U*", amount 1kg. Transportation is considered to the closest plastic recycling plant, with transportation recorded as "*transport, freight, lorry 3.5-7.5 metric ton, EURO5 {RoW}| Cut-off, U*", amount 66 kgkm. Avoided products here are, as in the case of ropes, "*polypropylene, granulate {RER}| production | Cut-off, U*", amount 1 kg and "*electricity, medium voltage {Europe without Switzerland} | market group for | Cut-off, U*", amount: 2,26 kWh. To obtain this value, the procedure was the same as above.

Cassettes are considered under waste treatment "*waste wood, untreated {RoW}| heat production, untreated waste wood, at furnace 1000-5000 kW | Cut-off, U*". Transportation in this instance is accounted for "*transport, freight, lorry 7.5-16 metric ton, EURO6 {RER}| Cut-off, U*", amount 42 kgkm, equivalent to the distance to the closest incinerator.

Finally, straw is assumed to be fully composted[17] using the waste treatment "*biowaste {RoW}| treatment of biowaste, industrial composting | Cut-off, U*", unit 1kg. The distance and transportation to the composting facility are accounted for by "*transport, freight, lorry 3.5-7.5 metric ton, EURO6 {RoW}| Cut-off, U*", amount 87 kgkm.

4.4 Life Cycle Impact Assessment

After the definition of the waste scenario, the next step was to assess the impacts of the production process. In order to better evaluate the contribution of each stage of the process to the overall environmental burden, five single LCA scenario were created, then the overall analysis performed. The methodology used for impact assessment is ReCiPe 2016 Midpoint (H) V1.03 / World (2010) H. The midpoint method is one of the most widely used (Patrik J. G. Henriksson, 2012). The hierarchist approach was chosen since it is the same used in the other LCA study on oyster farming in Italy.

Regarding procedure, in SimaPro this operation is performed by calculation of impacts for a LCA scenario composed of the inputs and processes, as well as the waste scenario. The impacts are calculated by the software program according to the methodology selected, then reported in a table and graphic format. The

[17] https://www.arpa.veneto.it/temi-ambientali/rifiuti/il-compost-in-veneto

network analysis is also available and provides more detailed information on specific input contributions. All impacts in this section refer to the reference unit, 1 kg of oysters after depuration and packaging.

As mentioned above in other sections, the impact indicators of relevance were the ones most widely used in literature (Nathan L. Pelletier, 2007) (Patrik J. G. Henriksson, 2012), namely climate change (under global warming in ReCiPe 2016), terrestrial acidification, eutrophication and fossil fuel consumption. To these four, two more were added, since they were considered in the other study on LCA of oyster products in Italy (E. Tamburini, 2019). For these categories, percentual contribution of the single production stages and inputs was considered. While the main focus rested upon these categories, other impacts are reported on the cumulative and stage-contribution level. All impact categories are reported in *Table 4*, with their overall and stage by stage contributions. The highlighted cells in the table indicate the categories studied more closely.

A graphical overview of results is also presented in *Figure 18*. From the graphic it is evident that the highest impacts occur regarding terrestrial, marine and freshwater ecotoxicity, and human toxicity both carcinogenic and non-carcinogenic.

Impact category	**Seed collection**	**Pre-fattening**	**Grow out**	**Depuration**	**Packaging**
Global warming	6,0783E-07	7,50702E-06	9,21872E-06	1,20019E-05	3,70658E-05
Stratospheric ozone depletion	4,32415E-08	3,53581E-07	2,24561E-07	1,33474E-06	4,44269E-05
Ionizing radiation	4,61183E-07	4,33754E-06	-4,03755E-06	3,13741E-05	4,02837E-05
Ozone formation, Human health	6,51694E-07	5,76544E-06	7,39383E-06	8,74597E-06	0,000126325
Fine particulate matter formation	7,48678E-07	5,65442E-06	7,76721E-06	6,47616E-06	3,79773E-05
Ozone formation, Terrestrial ecosystems	7,78351E-07	6,95595E-06	8,99649E-06	1,02909E-05	0,000148172
Terrestrial acidification	1,00176E-06	5,04377E-06	4,79577E-06	1,69896E-05	9,18693E-05
Freshwater eutrophication	1,21854E-05	4,30854E-05	2,59731E-05	4,30603E-05	0,000208217
Marine eutrophication	1,14849E-07	1,65503E-06	1,00506E-06	4,38554E-07	0,00017813
Terrestrial ecotoxicity	0,000201046	0,000795936	0,001874675	6,46182E-05	0,001340871
Freshwater ecotoxicity	0,001191297	0,006875567	0,002702729	0,000892195	0,007295305
Marine ecotoxicity	0,002051756	0,011752599	0,005225322	0,001491932	0,00950005
Human carcinogenic toxicity	0,000256787	0,001216138	0,001126165	0,000745955	0,003455855
Human non-carcinogenic toxicity	0,000326038	0,00123816	0,000901726	0,000197977	0,005906368
Land use	1,81966E-08	3,11069E-06	3,37767E-06	4,5922E-07	0,000175942
Mineral resource scarcity	1,57231E-09	4,22918E-09	5,39734E-09	5,76127E-10	6,07859E-09
Fossil resource scarcity	2,04757E-06	1,94545E-05	2,49005E-05	2,72424E-05	6,50824E-05
Water consumption	1,41835E-07	1,34919E-06	2,01473E-06	6,64965E-06	1,9097E-05

Table 4 - Results of the impact assessment analysis

Three main impacts were investigated using the network results, in order to identify which impacts were most responsible. All results are reported in *Table 5*. Pictures of the headers of network results for all impact categories of relevance are reported in *Annex 2*.

The first one under analysis was global warming. Inputs were inspected under a zoom factor of 5%. In SimaPro, lower aggregation levels were harder to understand and showed too many branches to be practical, while a 5% aggregation level was easy to grasp and showed practically the main contributions. The most impactful production process regarding global warming was the packaging stage, with the production of inputs having a 41.20% contribution to overall impacts. Second most impactful was depuration at 18.10%, then grow out at 13.90%. Here, the disposal of material products produced a negative result. When inspecting more closely the relative influence of single inputs over the total, the most relevant ones are straw lining, which accounts for 25,20% of the total, and electricity, accounting for 18%.

The second impact category more closely investigated was terrestrial acidification, expressed in kg of SO_2 equivalents. Again, the packaging stage shows the most contribution, accounting for 76.7% of total impacts. Both the material inputs and their disposal have a significant share. The second and third most impactful stage are the same as under global warming, so depuration at 14.2% and grow out at 4.01%. Single inputs were inspected again, and straw lining remains the most impactful process, contributing to 41,8% of the total. Next, the disposal of cassettes was the second most contributor, with 16,5% share of the total impacts.

Marine eutrophication, expressed in kg of N equivalents, was the third impact category inspected more closely. Here packaging represents almost the only contributor, with straw lining representing 98% of total impacts. Further inspection was deemed to be irrelevant after this result. Inspecting the results at smaller aggregation levels yielded no further results.

After marine eutrophication, fossil resource scarcity was inspected. While the most relevant production stage for this type of impact was, again, packaging, prefattening also became a relevant stage. Packaging is responsible for almost all of total impacts, with depuration, grow out and prefattening covering the other half. PP ropes are the single most contributor of impacts, with 28% of total impacts, followed by electricity and straw.

Stratospheric ozone depletion, expressed in kg of CFCC11 equivalents, would be caused mostly by packaging stage, in particular by the straw lining production. Disposal of inputs under stages depuration and packaging were significant as well. While packaging represents a 95,8% contribution to the total, further analysis was possible only after aggregation at 2%.

Lastly, marine ecotoxicity completes the list of most cited impact categories. Here, the biggest contribution is represented for the first time by the prefattening stage, with the disposal of lanterns showing a 23.5% share of the total contribution. Packaging and grow out were also significant stages. Boat motor is the most impactful single factor (28,7%), followed by disposal of lanterns and disposal of cassettes.

Impact category	**Unit of measure**	**Seed collection**	**Prefattening**	**Grow out**	**Depuration**	**Packaging**
Global warming	Kg CO_2 equivalents	0,9%	11,3%	13,9%	18,1%	55,8%
Terrestrial acidification	Kg SO_2 equivalents	-	-	4,01%	14,2%	76,7%
Marine eutrophication	Kg N equivalents	-	-	-	-	98%
Fossil resource scarcity	Kg oil equivalents	-	14%	17,9%	19,6%	46,90%
Stratospheric ozone depletion	Kg CFCC11 equivalents	-	-	-	2,88%	95,8%

Marine ecotoxicity	Kg 1,4-DCB	-	39,1%	17,4%	-	31,6%

Table 5 - Impact categories under focus

After closer inspection of the impact categories above and after consideration of the graph showing the absolute results for all impact indicators, inspection of freshwater ecotoxicity, human non-carcinogenic and carcinogenic toxicity and terrestrial ecotoxicity was performed. An overview is provided in *Table 6*.

Freshwater ecotoxicity is mostly influenced by the packaging stage, which represents a 38,5% contribution. Next in contribution terms are prefattening and grow out stages. The most impacting unit factor is the construction of the motor for the boat, followed by disposal of lantern nets and disposal of cassettes.

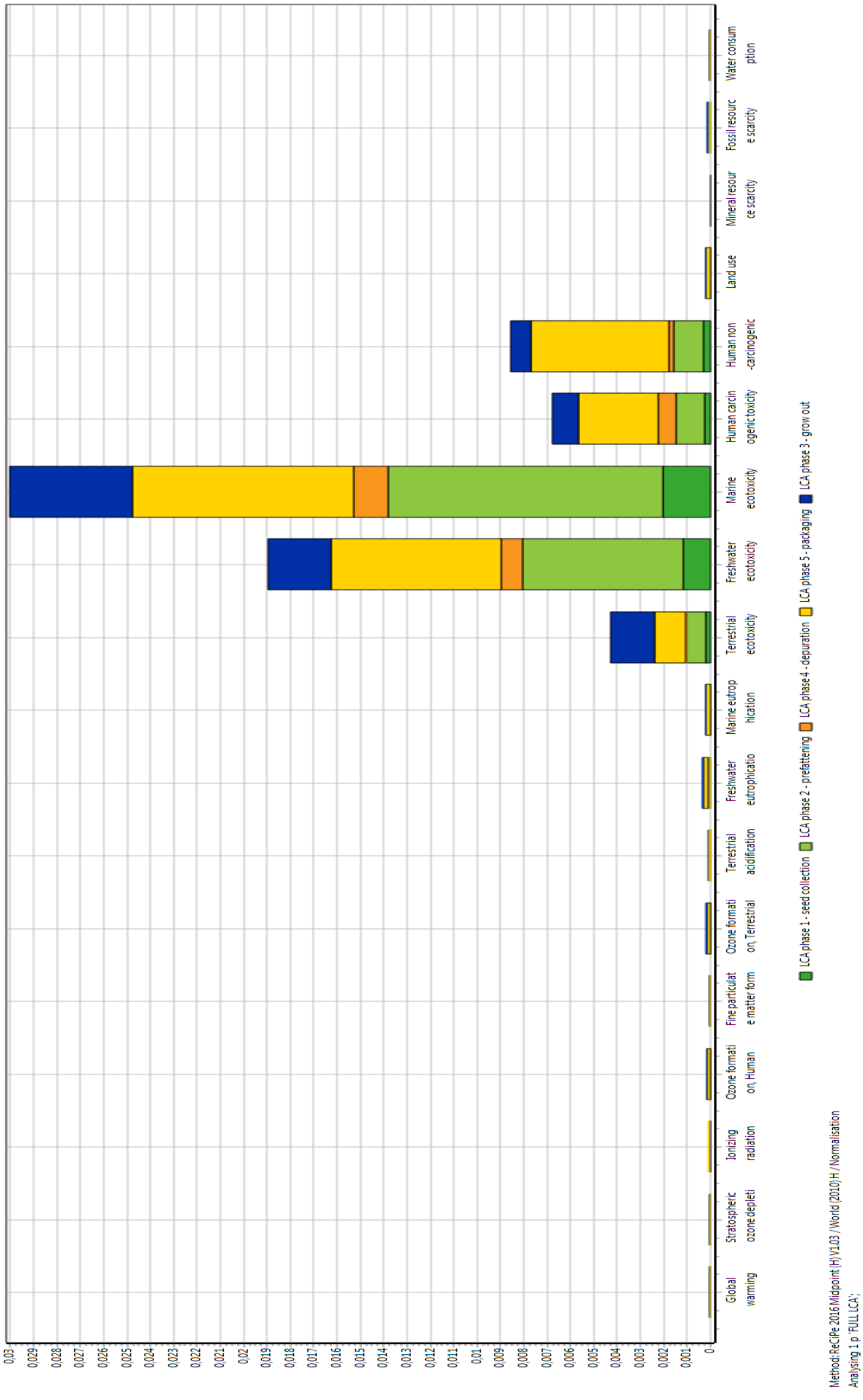
Human toxicity showed similar patterns for both carcinogenic and non-carcinogenic categories. The most significant stage is, again, packaging, followed by prefattening and grow out. Straw lining was the most relevant factor for non-carcinogenic toxicity at 44,4%, while cassettes were the most relevant input for 19,5%.

Finally, the last impact category thoroughly inspected was terrestrial ecotoxicity, measured in kg 1,4-DCB. The most relevant production stage is grow out (43,8%), then packaging and finally prefattening. Disposal of PP ropes is the most significant single factor with 42,7%. Boat motor is also relevant at 19,2%, then disposal of cassettes at 16,7%.

Impact category	**Unit of measure**	**Seed collection**	**Prefattening**	**Grow out**	**Depuration**	**Packaging**
Freshwater ecotoxicity	Kg 1,4-DCB	-	36,3%	14,3%	-	38,5%
Human non carcinogenic toxicity	Kg 1,4-DCB	-	14,4%	10,5%	-	68,9%
Human carcinogenic toxicity	Kg 1,4-DCB	3,78%	17,9%	16,6%	11%	50,8%
Terrestrial ecotoxicity	Kg 1,4-DCB	-	18,6%	43.8%	-	31,3%

Table 6 - Most relevant impact categories

Figure 18 – Below, graph of normalised impact categories.


Global warming
Stratospheric ozone depleti
Ionizing radiation
Ozone formati on, Human
Fine particulat e matter form
Ozone formati on, Terrestrial
Terrestrial acidification
Freshwater eutrophicatio
Marine eutrop hication
Terrestrial ecotoxicity
Freshwater ecotoxicity
Marine ecotoxicity
Human carcin ogenic toxicity
Human non -carcinogenic
Land use
Mineral resour ce scarcity
Fossil resourc e scarcity
Water consum ption
0
0,001
0,002
0,003
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LCA phase 1 - seed collection
LCA phase 2 - preflattening
LCA phase 4 - depuration
LCA phase 5 - packaging
LCA phase 3 - grow out
Method: ReCiPe 2016 Midpoint (H) V1.03 / World (2010) H / Normalisation
Analysing 1 p 'FULL LCA';

4.5 Interpretation

The interpretation stage in any LCA process should be used to evaluate results, in the end, but also continuously and critically evaluate the assessment and core assumptions. In this sense, it was used to refine the goal of the project. Initially, in fact, the scope of the present work was to offer a first assessment of environmental impacts of a new oyster product from a farm in Chioggia and then to roughly estimate the price of such product, considering a premium for the low environmental impacts of a local farm. This second goal was not possible; therefore, the project goal was adjusted.

Regarding results, the most significant impacts are due to the packaging stage of the production process, as illustrated both by *Table 4* above and *Figure 18*. This is not surprising, since many consumables are employed in the process, including straw which is a sub-product of agriculture production. A second impactful stage is the pre-fattening stage, while grow out seems to be less important. Seed collection is negligible, while depuration, even if most equipment was not accounted for, shows a significant burden on the environment. This may be due to the high electricity demand of the plant, powered by the grid and not relying on any form of renewable, self-produced energy. In this context, a reassessment of the machinery and an estimate of their composition are even more in order. Impacts could prove to be considerably higher, even after scaling against service life of around five years.

In absolute terms, the most significant impact category is ecotoxicity, as seen in *Figure 18* above, followed by human toxicity. At first, the analysis was not intended to focus on these impact categories. However, after inspection of results, a closer look was necessary. Freshwater toxicity is due to packaging and pre-fattening stage, which combined represent almost 80% of the environmental burden. In particular, the top five single factors at play are the boat motor, disposal of lantern nets and cassettes, the production of straw and of the cassettes. It is evident that waste scenario and treatment must be critically reviewed by future work.

Terrestrial ecotoxicity shows a different pattern, in the sense that the major contributor is the grow out stage. This production step represents almost 44% of total impacts, with the disposal of PP ropes being the single most relevant factor (42,70%). It must be noted that disposal is considered to be partly landfilling and partly recycling. An improved estimation of the waste treatment for the ropes as well as for all the other inputs could lead to different results. Prefattening and packaging are the most impactful production stages relative to marine ecotoxicity, with production of boat motor, disposal of lanterns and of cassettes being the most burdensome single factors in the production process. The fact that end-of-life treatment of material has a significant role in the ecotoxicity indicators is not a surprise since disposal of chemicals and treatment of possible chemical contaminations is key in prevention.

Human carcinogenic and non-carcinogenic toxicity are both expressed in kg of 1,4-DCB (1,4-Dichlorobenzene). Under both categories, the packaging stage is the most significant one, representing in the first case 50,80% of the total and 68,90% in the second case. Non-carcinogenic toxicity is mostly caused by the production of the straw – probably due to fertilizers – of the boat motor and by the disposal of cassettes. In the waste treatment stage, cassettes were estimated to be burned, since they would likely be treated under the "undifferentiated" share of urban waste[18] and the Veneto region has an incinerator plant operational. Carcinogenic toxicity is contributed to by almost all production stages, although the most significant one is by far packaging. Under single factors, production of cassettes and the motor of the boat seems to be the most relevant ones.

[18] In Italy there is door-to-door collection of waste. Usually, waste is categorized into compostable, plastic, aluminium, cardboard and paper, and undifferentiated. Every province has its own specific classification, though. Overall, it is likely that a wood cassette would be disposed in the undifferentiated category, unless the consumer had the possibility to dispose of it in other ways (e.g., by burning it or by disposing it with the cuttings and prunings and gardening waste).

After analysis of results of the "spikes" in graph X was conducted, the focus shifted to the original impact categories of interest, namely global warming, terrestrial acidification, fossil resource scarcity, marine eutrophication, and stratospheric ozone depletion. These are also the most cited impacts in literature (Patrik J. G. Henriksson, 2012).

Packaging and depuration account for over 70% of global warming impacts. Straw lining is the most significant input, followed by electricity used in the depuration plant. Straw is a sub-product of wheat farming, and extensive monoculture makes abundant use of fertilizer, produced with fossil fuel resources. Furthermore, electricity mix in Italy is trumped by gas and oil, while only around 20% of electricity is produced by renewables (IEA, 2020).

Terrestrial acidification and marine eutrophication are both caused mostly by packaging, again, which testify to the relevancy of this production stage in overall impacts contribution. Straw is the most relevant input in both categories, but cassettes disposal and electricity usage also represent significant contributors to acidification.

Fossil resource scarcity is mostly influenced by packaging as well, unsurprisingly, with PP ropes and electricity representing the most relevant contributors. The same observations made for global warming hold also here.

Finally, stratospheric ozone depletion was the last category under closer scrutiny. Packaging represents, once again, the lion's share of impact contribution (95,80%). Straw is the most relevant single contributor to the overall impacts.

It seems clear that the new production chain should put its sustainability focus on the packaging options for the final product, striving to minimize resource consumption as well as the use of plastic of fossil fuel origin. Electricity consumption is a second impactful hotspot, which could be addressed by installing PV panels on the roof and self-produce part of the electricity used. Alternatively, opting for an energy mix based mostly on renewables could be a solution. Addressing disposal of equipment as well as possibly considering equipment made of reused or recycled material should be another priority. By minimizing the impact of the end-of-life treatment of many material inputs could contribute to lowering the overall environmental impacts of the plant. Some stressors act outside of the control of the production chain: disposal of cassettes and straw, which proved relevant in the impact assessment. There is no easy way to address this issue. One possibility is to partner with the province and waste treatment companies to raise awareness on disposal of these materials. Such option is, however, outside of the scope of the work.

Chapter 5: Discussion

5.1 General considerations

The model presented in this work relies on a variety of assumptions that deeply influence results. In the previous sections, I listed the ones relative to the production chain, such as the successful restoration of natural oyster beds, collection rate, production periods. The analysis also has limitations relative to the inventory, which will be listed below. In short, it was not possible to access information on all the involved inputs. This problem could be addressed in further research, or once the production chain is created. Another level of difficulty was added by the fact that oyster farming is not very common in Italy at present times (Giovanardi, 2018) (Bronzi P., 2011). This led to almost no article being found regarding oyster farming in Italy. Literature on other countries and other species was more abundant. Finally, there was a time gap in availability of information from the Croatian counterpart. Although time considerations were made, this made the collection of data more complex.

Overall, the main limitation of the present work is data quality and general data availability. While information was available in the literature regarding methodological approaches and farming techniques – although the Venetian farming system was not present among them – data regarding precise numbers on required materials such as nets and collectors was absent. The existing oyster farm should have covered this gap. Since the farm is not operational as of yet, this was attempted by engaging with another local oyster farm and with a Croatian project inside the NORA network (NORA, 2017). Although precious information was gathered through this approach, a double-check with the existing farm would have provided a more reliable source of data. This regards not only precise numerical quantities of materials employed in the farming process, but also precise material composition, origin, and disposal. Considering that many of these information was not available – or could be found only in generalist websites – many approximations were required.

5.2 Data quality and assumptions

The inventory stage is one of the most time-consuming of the entire assessment (EU Joint Research Centre, 2010). This work was no exception. Gathering the information was difficult considering that the system under study needed to be modelled from scratch. Despite literature review and the possibility to question real-time practitioners, both Italian and Croatian, the author has no former knowledge of aquaculture and oyster farming. The physiology of oysters was also a new topic. Therefore, the modelled system may not be entirely realistic. Furthermore, the fact that the production chain does not exist as of yet made it harder to collect or estimate data. In doing so, the guiding criterion was to always use data from other *Ostrea edulis* farms whenever possible. Second-best data source was information gathered from the other Venetian oyster farm, which however uses a different farming technique (long-line) and farms a different species (*Crassostrea gigas*).

The most important estimate, however, is the quantity of output produced by the farm. This number influences all other calculations and estimates in the project. This is an obvious remark, but it is crucial, since just by adjusting it almost all results would change. In fact, the estimate output of oysters (20,160 kg) has been used to calculate the allocation coefficients for farming and depuration, the number of oysters produced, the number of collectors, lantern nets, cement and rope required, as well as the number of cassettes which would be used in the packaging stage. As mentioned in previous sections, the estimate was conducted jointly with Dr Boffo and based on information provided by the other Italian oyster farm and assumed to be 20-25% the quantity of mussels currently produced by the farm. The other farm, however, produces oysters of a different species and using a different farming technique entirely. This estimation was adopted regardless because environmental conditions are more similar to Chioggia ones rather than Croatian environmental conditions. Since this estimate constitutes the core of the project, this could be the first number to be critically reviewed in future works. Naturally, having real-time data would be the perfect way to check and validate the estimate.

Material composition was estimated as closely as possible considering that, for example, composition of coupelle collectors was not available even on producers' websites. Same can be said of lantern nets. In both cases, the assumption was high-density polyethylene. No metal components were considered for the nets, no other plastic grade for the coupelle collectors. A better approximation could be performed once the system is operational and an actual suppliers could be surveyed on the matter.

A blatant absent from material estimation is the equipment required for the depuration process. It was not possible to estimate the composition or weight of the equipment based on the information received by the farming plant. The farming plant provided a flyer with maintenance procedures as well as a brief description of operations conducted by each machinery. The information was not enough, however, to estimate a precise composition of the equipment, most importantly because all weight information was absent. The manufacture of the depuration equipment was identified and contacted, but the representative surveyed did not agree to share any kind of information, not even regarding the percentage in weight of, e.g., steel, glass, plastic or similar. Therefore, the analysis was conducted researching background data in SimaPro. Only UV filters were found and input. The input quantity was, however, of one unit since no information was available on the number of UV filters in operation at the plant. Bins were grossly input with their unit weight and material composition (HDPE).

Waste treatment is the section where the biggest approximations were made. This is certainly something which needs to be the area of focus for a review of the project. After trying a literature review, it was clear that an insufficient background knowledge was a limiting factor in understanding different waste treatment possibilities and pathways. The different treatments for steel remanufacture, as well as manufacturing processes aimed at specific functionalities were beyond the author's grasp and possibilities. However, the collaboration of someone keener on the topic, or a reconsideration of the process would be helpful in correcting the most gross assumptions. Waste treatment has a considerable influence in some of the impact categories under analysis, as became clear after the LCIA stage. Therefore, a future study would need to focus more accurately on waste treatment and recycling possibilities.

The functional unit was chosen to be 1kg of oysters at gate for two orders of reasons: it was the functional unit adopted in only other LCA study on oyster farming found relative to Italy, and it was a sensible choice considering that oysters are normally sold by the dozen, which is equivalent to 1kg approximately[19]. By choosing a similar functional unit to that of the other Italian study, comparison would be easier, although both farming technique and species farmed are different.

The allocation coefficients for both the depuration and the farming stage were defined based on a simple mass proportion. Mass was adopted even though price is commonly used in allocation (Fulvio Cellura, 2011),

[19] Different website surveyed: (I love ostrica, 2022), (Ostriche online, 2022), and others throughout the project.

mostly because of the ISO standards recommendations (ISO, ISO 14040, 2006). When describing the approach, the standards recommend leaving price allocation as last resort. Since in this project, mass was a more viable option, price allocation was discarded. There were other reasons as well. First of all, the production process does not exist yet and it was not possible to perform a price estimate for the oyster product[20]. Using a price allocation would have thus required diluting the results with an additional big estimate, based only on current market value rather than production costs and profit margin. This procedure would have reduced the reliability of the results, so it was eventually discarded. Finally, the farming system has two main outputs: oysters and mussels. In order to allocate impacts to two quite different products and not having a fully operational system to study, the easiest way to differentiate contributions was to use mass allocation. Further research could employ different criteria once the system is operational.

Regarding the second allocation coefficient, the molluscs treated by the depuration plant are three, each with its distinct price. Allocation by price would have only complicated the process, while not adding a really informative outlook. Future work may choose to opt for the price allocation and come to different conclusions.

A different approach on the functional unit would have been possible as well: using energy or protein content of the oysters. This is a common choice for many LCA-based assessment for animal products (X.P.C. Vergé, 2012) (thinkstep NZ, 2021). This approach was not adopted since both the energy content and the protein content are calculated based on the weight of any food product. The output considered in the project was already an estimate and conducting calculations on top would have reduced the amount of information associated with the results. The production estimate was not based on a real seed collection, nor on an existing oyster farming plant in place in Chioggia, but on primary data from other facilities and value chains. As such, calculating the protein content or the energy content associated and only then referred all inputs to the functional unit was not going to provide a more precise result.

5.3 Comparison with the literature

Tamburini et al. assess a long-line farming plant for Crassostrea gigas located in the Veneto region. The functional unit of choice allows for comparison, as well as the methodology chosen to conduct the assessment. Tamburini et al. calculate impacts using ReCiPe midpoint (H) v.1.12 method, while the present work uses ReCiPe 2016 Midpoint (H) V1.03 / World (2010) H, which was the latest available in the SimaPro version used. *Table 7* shows that the environmental impacts considered by both works are the ones most commonly found in aquaculture LCA analysis (Patrik J. G. Henriksson, 2012). The hypothesis from which Tamburini and colleagues move are that production is at steady state (no set-up years are considered), seed is provided by a hatchery, output is of about 8 tons of oysters per year. All data they use relies on existing conditions, since the farm is already operational. The paper analyses two scenarios, a current and an alternative one, where the difference is the location of the hatchery. In the current scenario seed is supplied by a French facility, while in the alternative scenario seed is sourced locally, but still from a hatchery. Impacts are calculated with two different methods, EcoIndicator 99-H and ReCiPe midpoint (H). EcoIndicator assesses

[20] Main reasons were: data not precise enough regarding farming equipment of choice, expenses held by the farm, market prices and species sold on the market. I surveyed websites of producers and retailers that sell oysters in Italy to roughly estimate the price of a dozen of oysters. Almost no oysters on the website were Italian, in accordance with market information (European Market Observatory, 2019). Almost no oysters on sale were *Ostrea edulis*.

impact at an endpoint level, while ReCiPe is employed for midpoint assessment. Only the alternative scenario is evaluated with ReCiPe 2016 midpoint (H).

The seed collection method in place under both scenarios has a significant impact on the overall results since hatcheries are very energy-intensive. Tamburini et al. does not consider depuration or packaging, while this present work does. This accounts for a significant methodological approach and a key difference in system boundary definition. Another consideration is the fact that the output quantity of oysters produced is quite small. Projected (and hoped) output from the Chioggia plant would be between two and three times that output. In this context, the results of the analysis are even more significant: impacts produced by the other Veneto plant are higher than those estimated for the Chioggia plant.

Impact category	**Tamburini (alternative scenario)**	**LCA results**	**Unit**
Climate change	1.85	6,64E-05	kg CO_2 equivalents
Terrestrial acidification	9.29E-3	1.2E-4	kg SO_2 equivalents / kg 1,4-DCB equivalents
Marine and freshwater eutrophication	1.38E-3	(freshwater) 0,000333 (marine) 0,000181 (total) 5.14E-4	kg PO_4 equivalents
Water depletion	31.76	0,0293	L

Table 7 - results of the impact assessment for present study and Tamburini et el.

Climate change was expressed as global warming under the version of ReCiPe 2016 used by the present study (v1.03), but impacts are expressed with the same unit of measure. The difference may be accounted for by the transportation requirements for seed that, even local, would still need to be moved from the hatchery to the farm, the different set-ups for farming, which could impact more in their production, as well as differences in the methodological approach.

Terrestrial acidification was expressed with different units of measure in the two studies: kg of SO_2 equivalents in Tamburini and kg of 1,4-DCB equivalents in this work, therefore impacts are not directly comparable between studies. More detailed information on results is provided only regarding the other methodology in use, EcoIndicator 99-H, which uses different impact categories and is relative to endpoint. Based on the other methodology, however, the most significant impacts on the ecosystem are due to the prefattening and fattening (grow out) stages of production, in particular to the barge employed in the farming process. In this work, most impacts in this regard are due to the prefattening and grow out but also to the packaging stage, while seed collection is irrelevant.

Water depletion is significantly smaller for the Chioggia plant. This result may be due to the fact that water is only needed in the depuration process and in relatively small quantities, then released back into the Lagoon after filtration. Instead, hatcheries require water for their operations, which would lead to an increase in use and demand.

Finally, Tamburini jointly considered freshwater and marine eutrophication et al., while the present work considers them individually. But, even if results are summed up together, the impacts on eutrophication are still one order of magnitude smaller than in the other study.

Conclusion

The present work started as ancillary research to the restoration project MAREA (Ca' Foscari University, 2022), which aims at restoring a natural oyster reef of the species *Ostrea edulis* in the Lagoon of Venice, more specifically near Chioggia[21]. Oysters of this species were once common in the Mediterranean and in Italy (Cataudella, 2011), but were driven close to extinction due to mismanagement and overconsumption. Restoration has gained traction in Europe, and *Ostrea edulis* has been the focus of considerable interest (NORA, 2017).

Restoration efforts focus on a section of the seabed located below a mussel farm. This location was chosen not only for its environmental conditions, but also because the presence of a farm above would protect the natural reef from trawling and dredging. Coincidentally, the placement offers the possibility to investigate compatibility between mussels farming and oyster restoration.

In the event that the restoration project should be successful, an oyster farming production chain based on the natural population could be set up in the existing mussels' farming plant. Seed collection could make use of the existing oyster beds, therefore eliminating the need for artificial hatcheries and increasing resilience and independence of the industry, while the farm could differentiate their income sources relying on two different animal products.

The present work moves from this possibility and aims at assessing the potential environmental impacts of the new production chain using the life cycle assessment methodology. The analysis is performed with SimaPro software program under version 9.0.0.49, using databases ecoinvent3 (cut-off by classification, unit) and agrifootprint. Impacts are calculated with ReCiPe 2016 Midpoint (H) V1.03 / World (2010) H. Therefore, direct impacts are estimated.

The first stage of this work was to study the oyster species under restoration, *Ostrea edulis*, which is the native European species now almost disappeared (J. Haelters, 2009). *Ostrea edulis* has a negligible market relevance at present, being the most caught of the two species produced in Europe (European Market Observatory, 2019) but with an overall small quantity. Oysters produced in Europe come mostly from farming and are of the species *Crassostrea gigas*.

Afterwards, the production chain was envisioned and modelled using information sourced directly or provided by practitioners: the veterinarian who currently works at the mussels' farm – Dr Boffo – practitioners from another project of the NORA network – located in Mali Ston, Croatia – and another farm in Veneto, which was contacted through Dr Boffo. Key support was offered by the co-supervisor, Dr Bertolini, PhD, as well.

The modelled farming process would farm oysters and mussels at the same time. Oysters farmed at the Chioggia plant would undergo three main farming stages and five production stages overall. These are the operations included in the system boundary of the analysis. The farming stages are: seed collection, pre-fattening and grow out.

Seed collection would occur from natural population, with coupelle collectors being placed in key locations surrounding the natural reef to optimize collection rates. Pre-fattening is the production stage in which small, baby oysters are brought to a size of about 30g. During this stage, oysters will be kept in lantern nets of two different sizes, depending on their dimensions. Finally, the last growth phase is done on ropes, where oysters

[21] Coordinates: 45°13'47.0"N, 12°15'58.6"E

are cemented in pairs and grown for almost a full year. Afterwards, oysters reach a marketable dimension and are harvested. Total farming time is estimated to be two and a half years.

After harvesting, oysters would need to be depurated since production area falls under depuration requirements in the Italian law (Regione Veneto, s.d.) (Federcoopesca, AGCI Agrital, Lega Pesca, 2011). Located close nearby to the farm is the depuration centre which would perform the operation. The depuration stage of the production chain was modelled after a guided tour of the facility. Unfortunately, modelling of the material inputs used in the system was harder than expected.

Finally, oysters would be categorized by weight into calibres (quality criteria for oysters) and packaged to be sold. This operation marks the end of the production chain included in the assessment.

After the modelling step, the focus shifts on the analysis. All stages of the life cycle assessment methodology were followed, starting with goal and scope definition. The boundaries of the system, which are the limits within which the analysis is performed, are defined as cradle-to-gate. Production of material inputs is included within the scope, but the analysis stops at the gate of the depuration centre, after which oysters would be shipped to retailers or end-consumers directly. The goal was set at the beginning of the project and is to conduct a first environmental assessment of the future oyster-based production chain.

Inventory stage is the operation of data collection. Primary information was always preferred whenever available, while data was checked against literature if uncertain. If no data were available from any of the other two sources, background data from SimaPro databases was used. The process was burdensome and lengthy, but cooperation from practitioners reached a satisfactory level.

After all data was collected, there was the impact assessment stage. Using ReCiPe 2016 Midpoint (H) V1.03 / World (2010) H, the calculation was performed with SimaPro, and all results evaluated. Interpretation was used throughout the project to check assumptions.

The results show a significant contribution of the packaging stage, which trumps all the other stages in relevance. Furthermore, the most significant impacts are not the ones most widely used in literature (Patrik J. G. Henriksson, 2012), but ecotoxicity and human toxicity. The results for the four most common impact categories were compared with another LCA-based study on oysters in Italy (E. Tamburini, 2019). Impacts from the other plant are on average one order of magnitude above the impacts of the Chioggia farm.

Waste treatment also plays a key role in weighting upon the impact results. As such, more work would be needed to fine tune the definition of the waste treatments. A sensitivity analysis could also be performed in this regard.

Overall, consumables showed a higher relevancy on impacts than components of the infrastructure, as expected. In particular, packaging materials such as straw lining and wooden cassettes are some of the most impactful single inputs evaluated in the calculations.

Despite the limitations of the present work critically reviewed in the Discussion chapter, the analysis clearly shows that the new production chain would have significantly lower impacts on the environment than a comparable local alternative, thus encouraging further work in this direction. A premium could also be considered in the final retail price in consideration of the results and the low overall environmental footprint. Further analysis and research are called for to better refine the first results obtained by the present study.

Cues for future research

Despite being remarked elsewhere, it cannot be stressed enough that future works could greatly improve on data quality and precision. First of all, a new and more precise output quantity needs estimation. This would be optimally done after the production process has actually started, to make use of real-time data. If this is not possible, or future studies are undertaken earlier than that, then partnering with a researcher in animal farming could prove helpful.

Secondly, the equipment used in the manufacture process needs to be described and input in the software program more precisely. If possible, the manufacture could be engaged at a higher level, perhaps by the university, to source precise information on material composition. Then, the waste treatment needs to be estimated more thoroughly and accurately. These are all possible improvements on data estimation and quality.

Regarding impact assessment, uncertainty analysis could be performed to check on the inputs' relevance, in an analogous way to what done by Tamburini et al. in their study (E. Tamburini, 2019). Also, inputs could be assigned to various scenario, depending on origin or composition of materials, to double-check on the influence of various assumptions. This could be done for waste treatment as well. The impact assessment procedure could also be performed in other ways: endpoint assessment could be analysed as well, and other impact assessment methods considered.

Future research efforts could opt for an alternative functional unit and verify whether results are along the same lines of present study or are greatly influenced by the change. Should protein content be chosen, a comparison could be made between the oyster product under analysis and other protein sources, like finfish, pulse, or other molluscs. This could be a highly informative result that could be used to market the final oyster product to local and national consumers.

Additionally, the carbon balance of oysters – relative to shell creation and respiration – was not considered in the present study but could be incorporated in future works.

Regarding the final product, performing a cost estimate could also be a new research possibility. Gathering cost information relative to the production process and using them to estimate a possible final price, as well as the margin of the farmers, could be the direct next step after the completion of this work.

When conducting the analysis, especially once the system is operational, growth and farming times could be reassessed. The full duration of 2,5 years is taken from the Croatian farms, which farm the same species in plants with a similar size. Instead, the other oyster farm in Veneto has growth periods of about 1,5 years. The species farmed there, *Crassostrea gigas*, has a shorter life cycle. However, a future analysis could employ farming time estimates more similar to the other Venetian plant and evaluate differences in the results of the analysis.

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