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Departamento de Enxeñaría Química

LIFE CYCLE ASSESSMENT OF MUSSEL AND TURBOT AQUACULTURE

Application and insights

Memoria presentada por:

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Para optar al grado de Doctor por la
Universidad de Santiago de Compostela

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UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Departamento de Enxeñaría Química

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Informan:

Que la memoria titulada "Life Cycle Assessment of mussel and turbot aquaculture. Application and insights" que, para optar al grado de Doctor en Ingeniería Química, Programa de Doctorado en Ingeniería Química y Ambiental, presenta D. Diego Iribarren Lorenzo, ha sido realizada bajo nuestra inmediata dirección en el Departamento de Ingeniería Química de la Universidad de Santiago de Compostela.

Esta memoria fue defendida el viernes 12 de marzo de 2010 en el Salón de Actos de la Escuela Técnica Superior de Ingeniería de la Universidad de Santiago de Compostela, ante el Tribunal compuesto por:

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Calificación: ***Sobresaliente Cum Laude.***

To my wife, parents and sister

Abstract

The path towards sustainability in the food sector demands the modification of the current operational and environmental patterns. In this sense, it is necessary to pursue reductions in the consumption levels for materials and energy, as well as the mitigation of the corresponding environmental impacts. Environmental management tools assist companies to monitor, manage and improve their environmental performance as well as to integrate environmental, economic and social issues. These tools enable the implementation of eco-efficiency strategies, life cycle thinking and environmental management systems into the business network.

In particular, Life Cycle Assessment (LCA) is a well-known technique for assessing the potential impacts associated with a product. One of the sectors where LCA has been widely implemented is the agri-food sector. However, while LCA in agriculture is quite well established, the use of this tool to assess seafood production systems is a more recent phenomenon.

This doctoral thesis contributes to widen the range of seafood species studied under an LCA approach. Furthermore, this dissertation develops new trends in LCA of seafood such as the combined application of LCA and Data Envelopment Analysis (DEA), or the implementation of Carbon Footprinting (CF) schemes.

The Galician fishing sector is a key economic branch in Spain. Within this sector, there is an activity where Galicia arises as the national leader. This is the Galician aquaculture, which can be understood as a sector itself. This dissertation evaluates two reference species in the Galician extensive and intensive aquaculture: mussels (*Mytilus galloprovincialis*) and turbot (*Scophthalmus maximus*), respectively.

The novel application of LCA to the mussel sector comprises a range of activities which can be grouped into four sub-sectors: mussel culture, dispatch centres, canning factories and cooking plants. Detailed inventories are presented for mussel farming, processing and consumption, as well as for the management systems regarding the valorization of mussel shells and mussel organic remains. From the environmental characterization of the Galician mussel sector, the main hot spots are identified and potential improvements are then proposed. The role of

mussel purification centres is highlighted together with the influence of vessel operation and capital goods on the potential environmental impacts associated with mussel culture. The environmental performances of fresh, canned and frozen mussels are also compared.

On the other hand, the application of LCA to the Galician turbot aquaculture is presented along with a previous LCA of feed for aquaculture. Thus, not only inventories for turbot farming and consumption are presented, but also inventories for the production of both marine and continental aquafeed. Therefore, recommendations for turbot farmers and also for aquafeed manufacturers are gathered on the basis of the environmental characterization results. Furthermore, a rough comparison between intensive and extensive aquaculture practices is established by assuming turbot and mussels as their respective representatives.

In this thesis, LCA is proved to be suitable for the assessment of the environmental performance of mussel and turbot aquaculture sectors. In this sense, LCA provides transparency and accountability all along the trade chain for mussels and turbot. Moreover, this dissertation gives insights on the potentials behind the use of CF and the combined application of LCA and DEA.

DEA is a performance measurement methodology used to empirically quantify the comparative productive efficiency of multiple similar entities. The combined application of LCA and DEA joins the strengths and minimizes the weaknesses attributable to both methodologies so that a synergistic effect is achieved while maintaining a quantitative character. This thesis links both methodologies and develops two LCA+DEA methods to be used depending on the objectives of the study. First, where eco-efficiency verification is pursued, a five-step LCA+DEA method is recommended. By using this approach, the connection between operational efficiency and environmental impacts is revealed, quantifying the environmental consequences of operational inefficiencies. On the other hand, if the aim is to directly compute environmental impact efficiency and target environmental impacts, then a three-step LCA+DEA method is proposed.

Finally, CF involves the estimation of the overall amount of greenhouse gas emissions associated with a product along its supply chain, even including use and end-of-life recovery and disposal. This dissertation discusses the potentials and drawbacks of CF while showing how to assess the carbon footprint of a certain canned mussel product according to the guidelines of an increasingly

popular specification named PAS 2050. Emphasis is laid on the relevance of CF to promote the establishment of policies based on life cycle thinking, support decision making in organizations and provide product differentiation. Furthermore, the detailed calculation of the carbon footprint of a common triple pack of round cans of mussels supplies a reference point for those mussel processors who are interested in the implementation of a CF scheme in order to attain competitive advantages and anticipate future regulations on global warming.

Keywords: aquaculture, aquafeed, Carbon Footprinting (CF), Data Envelopment Analysis (DEA), environmental impact, Life Cycle Assessment (LCA), mussel, *Mytilus galloprovincialis*, *Scophthalmus maximus*, turbot

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SECTION I.

INTRODUCTION TO THE STUDY

Chapter 1

Introduction to the Galician aquaculture sector

Summary

This first chapter tries to contextualize the doctoral thesis within the Galician aquaculture sector. The role of this sector inside the food industry framework is discussed and some economic data are provided.

The mussel sector is presented as the main representative of the Spanish extensive aquaculture. A description of this sector is detailed by focusing on the Galician experience due to its outstanding position in the mussel market from a worldwide perspective.

On the other hand, the national intensive aquaculture of marine fish is here represented by the turbot sector. Once again, Galicia sets itself up as a key region in the cultivation and commercialization of this seafood, not only from a national scale but also from an international scope.

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1.1. The food industry in Spain and Galicia

The net sales of products from food industry in Spain accounted for more than 78,000 million euros in 2007 (Sainz et al. 2008). This value meant a percentage over 14% of the total net sales for the Spanish industrial sector.

Table 1.1 gathers the main information concerning the Spanish food industry. As observed, the role of the seafood branch within the food industry cannot be ignored since it contributed with a percentage of 5% to the net sales of products as well as to the consumption of raw materials and to the number of employees.

Table 1.1. *Basic information for the food industry in Spain in 2007 (adapted from Sainz et al. 2008)*

Sector	Net sales of products		Consumption of raw materials		Employees	
	Million €	**%**	**Million €**	**%**	**Number**	**%**
Meat industry	15,904.67	20.20	10,542.63	23.84	85,624	22.41
Seafood transformation	3,626.50	4.61	2,257.92	5.10	22,248	5.82
Canned fruits and vegetables	6,265.58	7.96	3,316.63	7.50	35,410	9.27
Fats and oils	6,225.30	7.91	5,089.52	11.51	10,860	2.84
Dairy industry	8,603.54	10.93	4,597.10	10.40	28,069	7.34
Mill products	2,637.75	3.35	1,928.34	4.36	6,879	1.80
Animal feed products	6,853.37	8.71	5,094.98	11.52	14,124	3.70
Bread, cakes and biscuits	6,044.94	7.68	2,218.94	5.02	84,704	22.17
Sugar, chocolate and confectionery	3,228.34	4.10	1,437.75	3.25	17,779	4.65
Water	5,067.11	6.43	1,990.44	4.50	14,985	3.92
Beer and stout	3,052.52	3.88	495,51	1.12	7,855	2.05
Wine	5,319.62	6.75	2,439.58	5.52	22,863	5.98
Other alcoholic beverages	1,690.88	2.15	1,064.09	2.41	5,327	1.39
Other products	4,205.92	5.34	1,747.98	3.95	25,444	6.66
TOTAL	78,726.04	100.00	44.221,41	100.00	382,171	100.00

It is also interesting to highlight the relevance of Research and Development (R&D) within the Spanish food industry. Thus, Figure 1.1 shows the distribution of novel products among the different sectors in 2007. As captured in this figure, there are relevant percentages associated with sectors where seafood is involved: frozen food (13.7%), refrigerated seafood (2.9%) and canned food (2.1%).

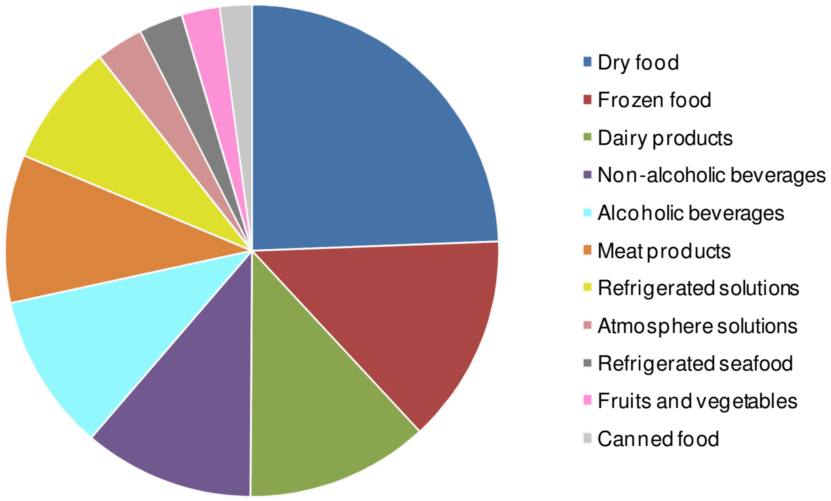

Figure 1.1. *R&D in the Spanish food industry in 2007 (adapted from Sainz et al. 2008)*

Turning to a regional scope, the food industry in Galicia (NW Spain) accounted in 2007 for 17% of the employees in the total industry sector, with around 29,000 employees. Moreover, when referring to the net sales of products, this percentage was of 18%, with more than 5,500 million euros. On the other hand, the consumption of raw materials in the Galician food industry involved 3,250 million euros, and the number of companies in this sector exceeded 2,600 (Sainz et al. 2008).

With respect to the economic turnover and the number of employees, seafood transformation was the industrial branch with the greatest contribution: around 2,000 million euros and more than 10,500 employees.

Finally, regarding the national food industry, Galicia accounted for more than 7% of the sales, with a similar percentage for the consumption of raw materials and with 8% of the employees.

1.2. The Galician aquaculture sector

The Galician fishing sector is the most important one in Spain. Its economic turnover exceeded 1,100 million euros in 2007, with a contribution over 10% to the regional gross domestic product (Sainz et al. 2008; Xunta de Galicia 2008a). Moreover, it is assumed that each direct employment within fishing activities involves four jobs inland.

The Galician fishing fleet is made up of more than 6,000 vessels, which means more than 40% of the national fishing fleet. Over 1,000 of these vessels are devoted to aquaculture.

The main commercialized species are sardine, horse mackerel, hake, turbot, mussels and other bivalves (cockles and clams), crustaceans (crayfish, barnacle, spider crab, etc.) and cephalopods (octopus and squid).

The Galician fishing sector consists of fishing, aquaculture and shellfishing. These branches support the seafood canning and freezing industry and, partly, the naval construction oriented to the construction, repair and maintenance of vessels. In addition to these activities, this sector also plays a role in the logistical distribution of seafood to the rest of Spain and other international destinations. This set of activities shapes an open complex with a strong exporting projection (Fernández & Fernández-Grela 2003; Fernández 2006).

Within the Galician fishing sector, the following industrial sub-sectors are highlighted (MAPA 2007a):

- Seafood canning. It is an activity oriented to export and is located along the Galician coast, mainly in the rias of Arousa and Vigo. According to data for number of establishments, production, turnover and number of employees, the relevance of the canning industry in Galicia is undeniable (ANFACO 2007). Currently, the Galician companies dominate the Spanish market and they are the reference in the European Union. In fact, around half of the national companies devoted to seafood canning are found in Galicia. In 2007, the Galician seafood canning sub-sector presented a production level close to 300,000 tonnes (85% of the total production in Spain), with the canning companies accounting for a turnover of more than 1,000 million euros and creating around 12,000 jobs.

- Naval construction. This branch comprises those factories responsible for the building, transformation, repair, maintenance and dismantlement of any type of ships, boats and floating appliances, as well as for the manufacture of engines, turbines, equipment, machinery and specific accessories for vessels. This sub-sector typically involves the delivery of individualized products in accordance with specific commercial orders, and works within a global market by means of industrial marketing channels (Xunta de Galicia 2008b).
- Seafood freezing. In this facet, Galicia is one of the most competitive places not only in Spain but also in the European Union. This top position is due to the great capacity of the Galician fishing fleet, the high professional qualification and the excellent features gathered by the port of Vigo with respect to logistics, storage and distribution of products.

Inside the fishing sector, there is an activity where Galicia arises as the national leader. This is the Galician aquaculture, which can be understood as a sector itself.

1.2.1. An introduction to aquaculture

Aquaculture is defined as a set of activities aimed at the culture of aquatic species. The objective of this farming is to produce species of commercial interest.

Three aquaculture modes are usually distinguished (MAPA 2007b):

- Extensive aquaculture (mollusc aquaculture). This aquaculture type differs from the rest of alternatives in that external feeding and medical care during the farming are both avoided. The most emblematic species within the national extensive aquaculture is the Galician mussel (*Mytilus galloprovincialis*). Galicia arises as the reference region in this field.

Figure 1.2. *Mussels from Galician rafts*

- Marine aquaculture (intensive aquaculture of sea fish). Spain is a country with a great coastal diversity which gives rise to a high-level specialization in the culture of sea fish, accounting for a wide range of operational procedures. The main species within the national marine aquaculture are gilthead bream, sea bass and turbot. In Galicia and along the Cantabrian coast, the turbot farming is developed in inland facilities with seawater supply. The Spanish regions with warmer water (Mediterranean and South Atlantic regions) cultivate gilthead bream and sea bass but with different production systems according to their orography. Galicia is the reference region concerning turbot (*Scophthalmus maximus*) aquaculture.

Figure 1.3. *Retail of turbot from aquaculture in Galicia*

- Continental aquaculture (intensive aquaculture of continental fish). In Spain, the development of this aquaculture variety is focused on the rainbow trout farming. To a lesser extent, tench, carp and sturgeon are other continental species being cultivated.

According to this classification, there are two aquaculture methods. On the one hand, extensive aquaculture is presented as a farming method mainly directed towards mollusc cultivation, which does not require the use of commercial feeds. On the other hand, intensive aquaculture is a method which includes the farming of sea fish as well as of continental fish, but demanding external feeding and antibiotic use. This dissertation involves the study of two reference species within the national and Galician extensive and intensive aquaculture: mussels (*Mytilus galloprovincialis*) and turbot (*Scophthalmus maximus*).

1.2.2. Aquaculture in Galicia

Aquaculture is highly developed in Galicia as the Galician coast presents perfect conditions because of the abundance of phytoplankton and its water temperature and healthiness, among other reasons. From the end of the seventies of the twentieth century, these features led to the development of an aquaculture industry described as regionally typical, diversified and in constant growth. Thus, Galicia holds a leadership position in the field of aquaculture.

In addition to these excellent natural conditions, Galicia profits from the availability of advanced technologies, a proved business experience in this area and a specialized training.

The main regional aquaculture practice consists of the extensive cultivation of molluscs in beds. In this sense, mussel culture (myticulture) is highlighted.

On the other hand, the Galician intensive aquaculture of fish is currently expanding. In fact, some companies located in Galicia are leaders in this branch even at an international scale. Here, turbot aquaculture stands out.

Figure 1.4. *Traditional mussel aquaculture in Galician rafts*

The Galician aquaculture production accounts for more than 80% of the national aquaculture production. Mussels and turbot are the main species cultured.

As shown in Table 1.2, the Galician aquaculture production exceeded 220,000 tonnes in 2007, with a turnover higher than 180 million euros. These values are extremely linked to the cultivation of mussels in rafts. Thus, this specific aquaculture practice accounted for 94% of the regional aquaculture production, and for 53% of the Galician aquaculture turnover (Xunta de Galicia 2008a).

Even though mussel cultivation prevails, flatfish intensive aquaculture should be also emphasized since it involved a production level close to 6,000 tonnes. In this sense, turbot farming entailed 95% of the intensive production and turnover. Furthermore, turbot culture accounted for 27% of the regional aquaculture turnover.

Algae cultivation is emerging as an increasingly relevant activity. It reached a production level of 11 tonnes in 2007. On the other hand, cephalopod culture is other important branch which involved the production of more than 24 tonnes.

Table 1.2. *The Galician aquaculture in 2007 (adapted from Xunta de Galicia 2008a)*

SPECIES	AMOUNT (kg)	TURNOVER (€)
Bivalve molluscs	215,463,510	132,038,483
Carpet shell	171,891	2,202,191
Grooved carpet shell	265,085	4,850,278
Manila clam	1,476,321	10,298,696
Cockle	1,131,057	2,977,842
Mussel	208,186,792	97,708,636
Mussel (culture parks)	21,608	30,538
Flat oyster	3,196,151	12,169,291
Cupped oyster	1,014,605	1,801,011
Cephalopods	24,663	145,131
Octopus	24,663	145,131
Fish	5,940,778	51,717,217
Pollack	39,660	124,765
Sole	40,332	488,798
Red sea bream	195,349	1,764,167
Turbot	5,665,437	49,339,487
Algae	11,100	8,410
Total	**221,445,461**	**183,933,384**

Mussels are the leading product of the sector. This bivalve mollusc is cultivated in rafts according to an extensive aquaculture procedure which demands minimal control by the farmer with no nutrient supply and without involvement during the reproduction process. The Galician rafts produce 98% of the mussels cultured in Spain.

Regarding the Galician intensive aquaculture, turbot is the main character. Its farming in Galicia accounts for around 90% of the national turbot production.

Table 1.3 breaks down the number of aquaculture facilities in Galicia in 2007. More than 3,500 rafts are anchored in the Galician rias; most of them are devoted to mussel culture. There are near 1,200 mollusc culture parks (mainly for carpet shell, grooved carpet shell and Manila clam). Finally, Galicia accounts for 22 marine farms and 17 beds for flatfish and molluscs.

Table 1.3. *Aquaculture facilities in Galicia in 2007 (adapted from Xunta de Galicia 2008a)*

RAFTS	3,515
Mussel	3,337
Oyster	107
Polyculture	71
MARINE FARMS	22
Flatfish	20
Molluscs	2
BEDS	17
Flatfish	7
Molluscs	10
CULTURE PARKS	1,190

1.3. The mussel sector

Aquaculture has emerged as a dominant sector in world fisheries due to its potential to balance the decline in available marine seafood resources (Ahmed 2003). The rapid growth in this sector is largely attributable to developments in aquaculture technology that have been encouraged by expanding international markets.

In the case of mussels, unlike most aquatic species, wild mussel production is much smaller than the cultured mussel production. In fact, mussel share in production roughly means 10% for mussel capture and the remaining 90% for mussel culture (Josupeit 2005).

Worldwide, mussels are mainly cultivated in floating structures called rafts, in long-lines and, to a lesser extent, lying on fixed structures on the sand and naturally attached to coastal rocks (Tirado & Macias 2006).

Table 1.4 shows the most important mussel producing countries. Worldwide, China is the main producer (Conde 2007). However, its mussel production is mainly intended for national supply and, surprisingly, its role in the production of canned or frozen mussels is not relevant (Josupeit 2005).

Table 1.4. *Overview of mussel production worldwide (Iribarren et al. 2010a)*

Country	Tonnes (2004)	Main method
China	717,368	Culture
Thailand	296,000	Culture
Spain	294,826	Culture
Denmark	99,500	Capture
New Zealand	86,353	Culture
Chile	78,845	Culture and capture
Italy	77,653	Culture and capture
France	74,100	Culture
Holland	67,200	Culture

World production of mussels steadily increased over the past decades, from about 700,000 tonnes in the 1970s to 900,000 tonnes in the 1980s. In 2005 world production had increased up to 1.8 million tonnes, of which roughly 30% was produced by the EU (FAO 2006, 2007). The Galician mussel aquaculture leads the European production with an outstanding percentage around 50%.

Actually, when considering the production of mussels intended for human consumption, Spanish mussels occupy the world's top position in sales since China is still developing this industry (Jian-Guang & Qisheng 2005).

As previously stated, activities related to the Spanish mussel sector are primarily located in Galicia where mussels are the single largest cultured shellfish and entail a strong impact on the Galician economy.

Rafts are the most common mussel cultivation system in Spain (Figure 1.5). A raft is defined as any floating structure constructed of wood or reeds, kept afloat using any combination of buoyant materials such as wood, sealed barrels, inflated air chambers or extruded polystyrene blocks. The main components of the raft are the grid (mesh of wooden beams), the flotation system, the anchoring system (shackle chain and concrete anchoring blocks) and the cultivation system (ropes with plastic pegs) (Tirado & Macias 2006).

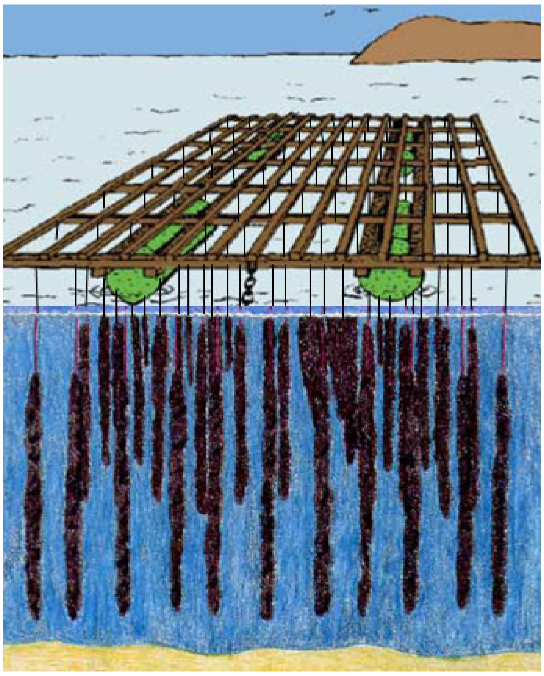

Figure 1.5. *Conventional raft for mussel aquaculture*

The activities performed in the raft include:

- Seed collection. Mussel farmers usually collect this seed from two different sources: coastal stock from the rocky shoreline and collector ropes suspended from culture rafts (Labarta et al. 2004). Another possibility consists of the use of netting strips submerged at 1-2 m depth during the reproduction period of the mussel.

- Seed pre-fattening. This operation is performed by attaching small seeds to the ropes with the aid of thin cotton nets. These ropes are submerged in the sea, hanging from the platform (Figueras 1989).
- Rope thinning. The thinning-out process is carried out when individual mussels reach a size of around 5 cm, generally after 4-6 months (Pérez-Camacho 1992). Three or four new ropes can be obtained from each initial rope, allowing the mussels to grow with a more homogenous shell length and a smaller density of molluscs per rope length until they reach commercial size (7-10 cm).
- Harvesting and selection. Growing ropes are hauled onto boats with hydraulic cranes and they are stripped of their mussels. Afterwards, the clumps of mussels are separated, washed with seawater, classified according to shell length and then bagged.

However, the mussel sector in Galicia is not limited to mussel farming. In fact, the Galician aquaculture of mussels (*Mytilus Galloprovincialis*) gives rise to a complex sector involving not only cultivation tasks but also a variety of processing activities. These activities are performed by different economic actors depending on the processing alternative selected for mussel transformation.

Thus, the role performed by the supplier companies implies an annual turnover of 8 million euros and 530 jobs, while dispatch centres have an annual turnover of 87 million euros and 500 jobs. Finally, mussel processing factories present a turnover of 66 million euros, providing 900 jobs (Franco 2006).

Three main sub-sectors can be assumed according to the centres where mussel transformation takes place (Iribarren et al. 2010b):

- Dispatch centres sub-sector. This branch is responsible for the fresh mussel market. A dispatch centre is any on-shore or off-shore establishment for the reception, conditioning, washing, cleaning, grading, wrapping and packaging of fresh molluscs for human consumption. The purification process consists of the maintenance of the molluscs for a certain period of time (at least 42 h) in water free of pathogens, so that these molluscs filter the water and get depurated (Amengual 1989). There are many agents and procedures to remove pathogens in seawater, being chlorine gas the most extended alternative worldwide (Plataforma Tecnolóxica 2007).

- Canning factories sub-sector. Galicia produces more than 80% of the canned seafood in Spain, with a marked position for tuna (Hospido & Tyedmers 2005), sardine and mussel. This latter is the most representative and commercialized mollusc in the Spanish market; around 73% of Spanish families consumes this product (Illescas et al. 2007). This second cluster produces canned mussels using mussels transported from the cultivation sites as the main raw material. Canning factories carry out a wide range of operations that could be sorted out as follows (Xunta de Galicia 2005): initial operations (mussel reception, washing and sieving, de-clumping, trimming, etc.), processing operations (cooking, mussel flesh separation, byssus removal, size grading, dehydrating, packaging, liquid dosage and filling, etc.), final operations (sealing, washing, codification, sterilization, washing and drying, cartoning and packaging, and storage) and ancillary operations (wastewater treatment, bathroom fittings, machinery maintenance, general cleaning, boilers and central heating).
- Mussel cooking plants sub-sector. This third group supplies several types of boiled mussel products. Two main categories are distinguished: frozen boiled mussels and canned mussels produced from boiled mussels. These two categories have the same intermediate product, i.e. the boiled mussel flesh, but different subsequent operations. Refrigerated/frozen boiled mussels are produced in cooking-freezing facilities, while canned mussels are usually produced in partial canning factories which process boiled mussel flesh coming from cooking plants.

The several components of each sub-sector will be detailed in subsequent chapters of this dissertation.

1.4. The turbot sector

The turbot sector mainly involves farms where intensive aquaculture practices are performed. Nevertheless, there are other components which play an essential role within the Galician turbot sector, as captured in Figure 1.6. These components include: (i) feeds, (ii) equipment, (iii) buildings, (iv) chemicals, and (v) energy carriers (Aubin et al. 2006).

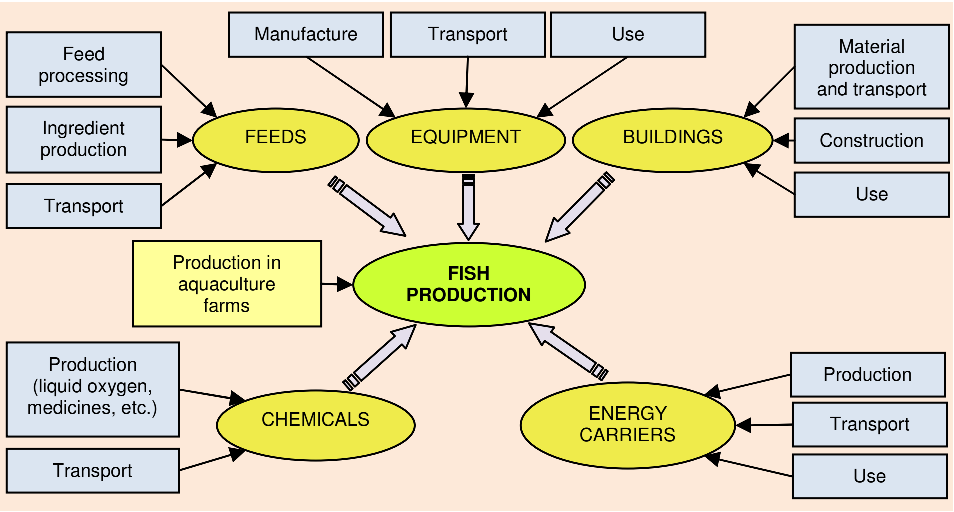

Figure 1.6. *Components involved within the turbot sector*

Regarding fish production, commercial turbot is produced in inland farms with seawater supply. In these facilities, turbot aquaculture is developed according to a set of stages from gamete obtention to final growing for commercial purposes (Garazo 2009).

The conventional steps performed in turbot (*Scophthalmus maximus*) farms are shown in Figure 1.7. Apart from feed production, the processes included in the figure are generally carried out in the concerned turbot farms.

The first stage is aimed at gamete obtention for both males and females. In their natural environment, turbots release gametes in spring or summer. However, aquaculture farms have turbot larvae and juveniles all the year because it is possible to induce egg lay by means of exposures at different light periods which promote sperm and ovule release. After six or eight fertilization days, larvae are obtained and they float on the surface of the tanks.

Larval development is a critical stage because of mortality. Therefore, in this phase, water quality, oxygen content, diet and physicochemical parameters such as temperature and light are carefully controlled. For instance, water must be filtered, heated and treated with ultraviolet light in order to remove microorganisms which can be detrimental and induce mortality. Larval development is usually performed in black round tanks where culture is developed with individual densities ranging from 30-40 larvae per litre of water. In Spain, intensive culture prevails for larval development.

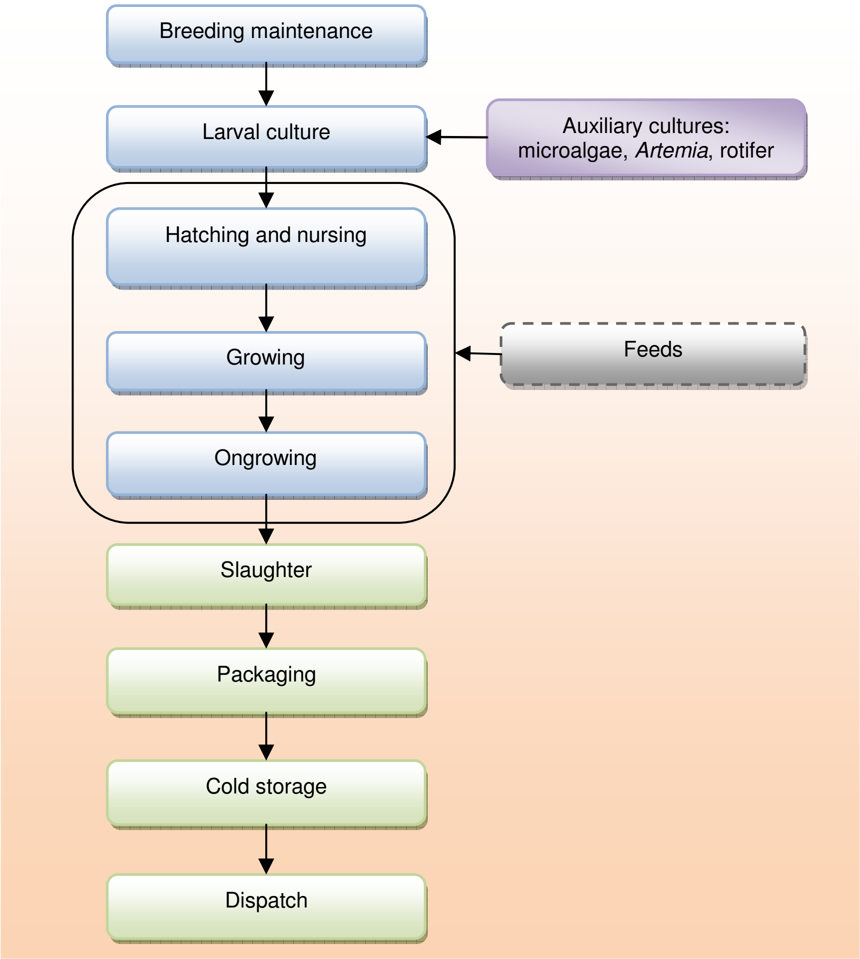

Figure 1.7. *Stages in turbot aquaculture farms*

After egg eclosion and for seven days, larvae feed themselves on the vitelum sack that they have when they are born.

Afterwards, the feeding of larvae consists of zooplankton which is produced in the farm itself. Initially, feeding is based on rotifers provided with phytoplankton. Then, they are fed *Artemia salina*. Larval growth is very rapid and, after 90 days, larvae go from 3 mm and 0.2 g to 35 mm and 2 g.

Turbot is a benthic species with flat shape. During larval development a metamorphosis takes place. This phenomenon begins from day 15 and lasts around 45-60 days.

Close to the end of the metamorphosis, larvae are moved to tanks with greater surface and lesser depth.

During this growth period, feeding is changed from zooplankton (live feed) to feed (inert feed). This change is called weaning. It takes place when the metamorphosis process is ending. If diets are appropriate, the survival percentages can be greater than 95% for this stage.

Growing happens from 0.5-1 g up to 5 g. Turbot juveniles are further developed in tanks with greater surface and lesser height than the initial ones. Physicochemical conditions are similar to those of the previous stage. It is important to keep a proper water renewal and to avoid dead zones in order to prevent diseases associated with waste accumulation. Feeding is feed-based.

The ongrowing stage lasts until turbot juveniles reach commercial size (adult turbots). This is the easiest period within the turbot culture. Survival percentages during this phase are the highest ones. Feeding is usually based on feed, just resorting to fresh food (low-value fish like blue whiting) when profitable. This culture stage is carried out in tanks with individual densities around 20-40 kg/m^2. Fish size grading is a key aspect during this step.

After 26-30 months, turbots reach commercial size, i.e. 1.5-2 kg. However, since females grow in a larger extent than males, the latter are usually commercialized when they are around 1 kg in weight.

For commercialization, turbots are removed alive from the cultivation tanks. Finally, they undergo a heat shock which leads to death.

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Chapter 2

Introduction to management tools

Summary

Once the study has been contextualized, this second chapter presents an overview of the management tools that facilitate the path of business towards sustainable development. The role of environmental management tools to assist companies to monitor, better manage and improve their environmental performance is highlighted. Specifically, Life Cycle Assessment (LCA) is detailed since it was chosen as the environmental management tool to evaluate the mussel and turbot aquaculture sectors from a life cycle perspective. Carbon Footprinting (CF) is also addressed because of its link with LCA and its current popularity in the food sector as a measure to promote climate change mitigation while providing environmental information. Additionally, Data Envelopment Analysis (DEA) is introduced due to its potential to establish proper eco-efficiency targets when used together with LCA.

The objectives and structure of this thesis are explained according to the framework established throughout these two chapters.

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2.1. Sustainable development

In order to understand the objectives of this document, it is important to know the framework which justifies the need and use of the current study. The previous presentation of the aquaculture sector contributes to define the context of the research but it is not enough to establish its framework. There is a concept lacking: sustainable development.

The term sustainable development was used by the Brundtland Commission to designate the development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations 1987). Therefore, sustainable development involves a pattern of resource use which aims to meet human demands while preserving the environment so that these needs can be met not only in the present, but also for future generations to come.

Sustainable development is conceptually regarded as the intersection of three constituent parts as shown in Figure 2.1. These three dimensions refer to environmental sustainability, economic sustainability and socio-political sustainability.

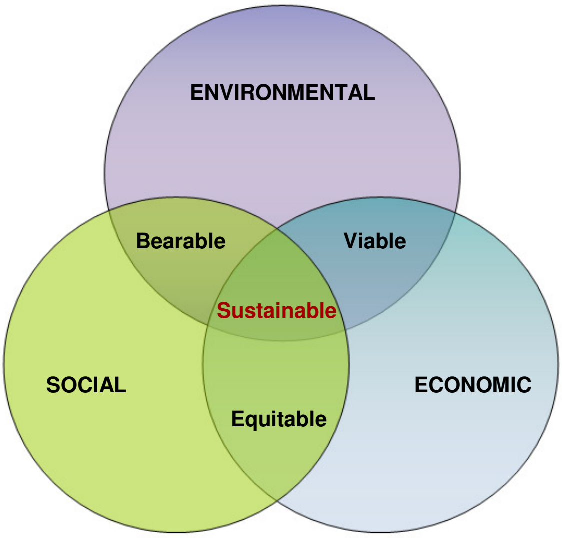

Figure 2.1. *Scheme of the three dimensions of sustainable development (adapted from Adams 2006)*

The path towards sustainable development demands the modification of the current operational and environmental patterns. In this sense, it is necessary to pursue reductions in the consumption levels for materials and energy, as well as the mitigation of the corresponding environmental impacts. Environmental sustainability is the ability to maintain the qualities that are valued in the physical environment. Sustainability requires that human activity only uses nature's resources at a rate at which they can be replenished naturally. The long-term result of environmental degradation is the inability to sustain human life. Under this perspective, numerous environmental management tools have been developed with the aim of minimizing the environmental impacts linked to products, processes and services (Feijoo et al. 2007a).

2.2. Environmental management tools

Concepts such as responsible entrepreneurship and eco-efficiency reveal the current trend towards sustainable development when dealing with business. Thus, companies should implement strategies that integrate the three pillars of sustainable development. These strategies consist of a joint application of environmental and economic efficiency together with the promotion of social responsibility. Environmental management tools have played, play and will play a major role in the establishment and confirmation of this trend.

Environmental management is focused on those activities of a firm that involve or may involve an impact on the environment. The advantages of performing environmental management include (Andersson 1998): (i) cost savings, (ii) legislative compliance, (iii) anticipation of future legislation, (iv) reduction of environmental risk, (v) fulfilment of supply chain requirements, (vi) improvement in relations with regulators, (vii) improvement in public image, (viii) increased market opportunities, and (ix) employee enthusiasm.

Environmental management tools were developed in order to facilitate the improvement of the environmental performance of companies and the integration of environmental, economic and social concerns. There is a wide range of environmental tools. They can support the evaluation of environmental impacts (e.g. Life Cycle Assessment), improve product development (e.g. eco-design), identify costs and benefits of environmental action (e.g. environmental accounts), raise awareness and communicate an environmentally and social responsible image to different stakeholders (e.g. environmental and social reporting), or measure progress and compare it with that of other companies (e.g. environmental benchmarking). Environmental management tools enable the implementation of eco-efficiency strategies, life cycle thinking and environmental management systems (such as EMAS and ISO 14001) into the business network.

In the early 1990s the International Organization for Standardization (ISO) identified the need for standardization in the field of environmental management tools. In 1993 a committee was set up to write standards regarding the following five environmental management tools (Andersson 1998): (i) environmental management systems, (ii) environmental auditing (withdrawn standard), (iii) Life Cycle Assessment, (iv) environmental labelling, and (v) environmental indicators.

Other relevant environmental management tools are environmental policies, ecobalances, environmental reporting and environmental charters.

2.2.1. Environmental management systems

An environmental management system (EMS) enables an organization to manage its environmental affairs in a comprehensive, systematic, planned and documented manner. Thus, firms can identify those ways of improving their environmental performance that most benefit their business performance.

The most widespread EMS schemes are the international environmental management system standard ISO 14001 (ISO 2004), and the European Community's ecomanagement and audit scheme EMAS (European Commission 2001).

An EMS follows a Plan-Do-Check-Act (PDCA) cycle. First, the organization must develop an environmental policy, plan the EMS, and then implement it. The process also includes checking the system and acting on it. An EMS is a process of continual improvement in which an organization is constantly reviewing and revising the system.

2.2.2. Environmental auditing

Environmental auditing (ISO 1996) is a tool for checking whether an organization is doing what it should be doing. Environmental audits are intended to quantify environmental performance and environmental position. An environmental audit report ideally contains a statement of environmental performance and environmental position, and may also aim to define what needs to be done to sustain or improve target indicators.

2.2.3. Life Cycle Assessment

Life Cycle Assessment (LCA) is a “technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study” (ISO 2006a, 2006b). In this definition, the term product stands for both goods and services. LCA adopts a “cradle to grave” approach pursuing the impacts of a product throughout its life cycle, i.e. from raw material acquisition (the cradle) through its production and use to its final disposal (the grave).

LCA is further explained in section 2.3 since its application and potentials are the core of this dissertation.

2.2.4. Environmental labelling

Environmental labelling schemes award an environmental label to those products that are judged to be less harmful to the environment than others within the same product group. To be awarded a label, a product has to meet a set of environmental criteria established for its product group by the labelling scheme organizer. The criteria relate to the complete product life-cycle and are drawn up using Life Cycle Assessment. Environmental labels are often used to gain market access and competitiveness.

The international standard ISO 14020 (ISO 2000) establishes guiding principles for the development and use of environmental labels and declarations.

2.2.5. Environmental indicators

Environmental indicators enable organizations to measure their environmental performance and their efforts to improve their performance. Environmental indicators are central environmental parameters that are associated with a certain activity. By following the development of an environmental indicator and comparing this with the production process, one can determine whether the environmental performance of a production process is improving or becoming worse.

The international standards ISO 14031 (ISO 1999a) and ISO 14032 (ISO 1999b) provide guidelines on the evaluation of the environmental performance of companies.

2.2.6. Environmental policies

An environmental policy is a document which clearly gathers the overall aims and intentions of a firm regarding the environment. The development of an environmental policy is often the first step for organizations which wish to undertake environmental management. An environmental policy involves a commitment to environmental management.

2.2.7. Ecobalances

A company ecobalance facilitates a comprehensive environmental review of the company activities. It is a record of the various raw materials, energy, resources, products and wastes entering, held within and leaving a company over a specified period of time, so that organizations are ready to assess their specific environmental impacts.

2.2.8. Environmental reporting

An environmental report involves the communication of the results related to the environmental management initiatives undertaken by a firm in order to improve its environmental performance. Issuing an environmental report can improve a company's public image and lead to improved relationships with stakeholders.

2.2.9. Environmental charters

An environmental charter demonstrates the company's commitment to responsible environmental management. By signing up to a charter a firm publicly declares its intention to carry out its environmental management activities in accordance with the set of principles contained in that charter.

2.3. Life Cycle Assessment

Life Cycle Thinking expands the traditional focus on manufacturing processes to incorporate various aspects associated with a product (i.e., any good or service) over its entire life cycle, recognizing that various impacts occur at all points along the life cycle of the product. In this sense, Life Cycle Management (LCM) is a systematic product management that aims to minimize the environmental and socio-economic burdens associated with a product during its entire life cycle and value chain (UNEP 2007).

A life cycle is made up of consecutive interrelated stages of a product system from raw material acquisition (or production from natural resources) to final disposal. Figure 2.2 symbolizes this concept by representing not only the processing of a certain product but also previous and subsequent stages such as production, transport, shopping, consumption and waste management.

Figure 2.2. *Life cycle concept*

A wide range of tools, techniques and concepts are available to provide information and data to be used in an LCM system. Among others (CHAINET 2008): (i) check-lists, (ii) cost-benefit analysis, (iii) cumulative energy requirement analysis, (iv) environmental impact assessment, (v) environmental risk assessment, (vi) input-output analysis, (vii) Life Cycle Assessment, (viii) material flow analysis, (ix) material intensity analysis, and (x) multi-criteria analysis.

As previously stated, LCA constitutes a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements (Consoli et al. 1993). LCA is one of the tools that have received much attention from both the scientific world and the policy makers. This dissertation discusses the application and potentials of LCA in the aquaculture field. Hence, additional relevant concepts on LCA must be introduced.

2.3.1. Introduction to Life Cycle Assessment

LCA tackles the environmental aspects and the potential environmental impacts linked to the entire life cycle of a product, encompassing all stages from cradle to grave: raw material extraction and processing; manufacture, transport and distribution; use; re-use, maintenance; recycling and final disposal. As represented in Figure 2.3, four stages are distinguished for LCA studies (ISO 2006a, 2006b):

- Goal and scope definition.
- Inventory analysis.
- Impact assessment.
- Interpretation.

Among the numerous LCA applications, the following ones are highlighted:

- Detection of opportunities to improve the environmental performance of products throughout the different stages of their life cycle.
- Information collection to support decision making within organizations (e.g. strategic planning, prioritization, product/process design or re-design, etc.).
- Selection of environmental indicators and measurement techniques.
- Marketing. For instance, by implementing an environmental labelling scheme, making an environmental claim or supporting a product's environmental statement.

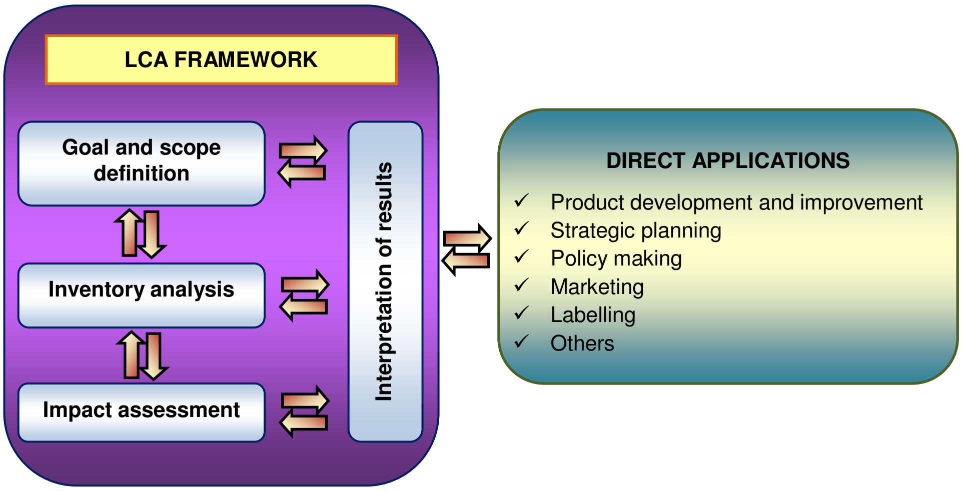

Figure 2.3. *LCA framework and applications (adapted from ISO 2006a)*

The four traditional stages for LCA studies are further explained.

Goal and scope definition

The goal and the scope of an LCA should be clearly defined and coherent with the application planned. Because of the iterative nature of LCA, the scope could be updated during the study.

The goal defines the potential use and audience of the specific LCA case study as well as its justification, while the scope establishes key aspects of the study such as product system, its functions, functional unit (FU), system boundaries, allocation procedures, impact categories, environmental impact assessment method, data requirements, assumptions and restrictions.

The FU (ISO 2006a) quantifies the functions of the target product. The main purpose of an FU is to provide a reference to which inputs and outputs are related.

An LCA is performed by defining product systems as models which describe the core of the physical systems. System boundaries determine the unit processes to be included within the system.

Data quality requirements specify the characteristics of the data needed for the study. Time, geography, technology, accuracy, completeness, consistency, reproductiveness, data sources and uncertainty are some of the aspects considered in data quality.

Inventory analysis

The life cycle inventory analysis stage demands an inventory of the input and output data for the system under study. Consequently, this phase involves data collection as well as the explanation of the calculation procedures used.

Qualitative and quantitative data are collected for each of the unit processes within the system boundaries. Collected data come from measurement, calculation or estimate, and are used to quantify the inputs and outputs of a unit process.

Among the measures to guarantee a proper understanding of the system product, the following ones are underscored:

- Making process flow diagrams in order to describe all unit processes and their interrelation.
- Listing the flows and operation data related to every unit process.
- Listing the units used.
- Describing the calculation and collection data techniques.

In 1991 the Society of Environmental Toxicology and Chemistry (SETAC) proposed a general flow diagram for life cycle inventory (Figure 2.4). This diagram comprises all phases in the life cycle of a process (Fava et al. 1991).

Inventory data collection is the most time- and resource-demanding step when an LCA is performed. Collection will be different depending on the specific context. Four groups can be distinguished regarding data acquisition (von Bahr 2001): (i) direct measures, (ii) published documents, (iii) electronic sources, and (iv) personal communications. Among these information sources, commercial databases have been and are still being one of the main tools for finding inventory data (Fullana & Puig 1997).

Data for each of the unit processes inside the system boundaries can be classified as: (i) energy inputs, raw materials, auxiliary inputs and other physical inputs, (ii) products, co-products and waste streams, (iii) emissions to air, effluents to water and waste to soil, and (iv) other environmental items.

On the other hand, every calculation procedure should be recorded and the related assumptions should be specified and detailed. The same calculation methods should be used throughout the whole study.

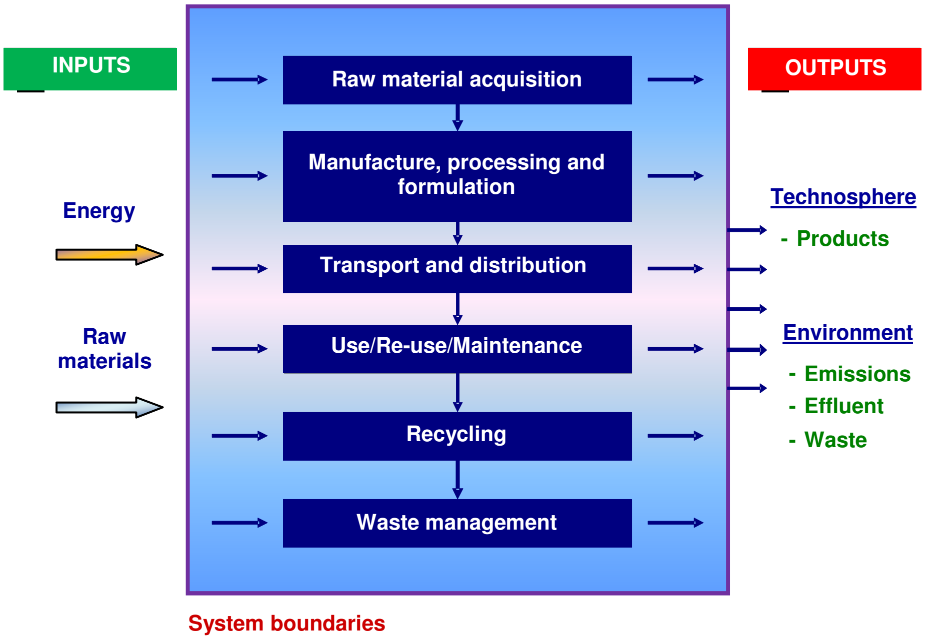

Figure 2.4. *Flow diagram for life cycle inventory (adapted from Fava et al. 1991)*

Given the relevance of allocation within this stage, some notations are introduced. In order to make a representative and reproducible system inventory, not only quality data is needed, but also a correct allocation of these data related to each of the subsystems to be evaluated (Feijoo et al. 2007b). A cause-effect relationship is established between raw material consumption/waste generation/system emissions and the activity or process which gives rise to the function being assessed. In the case of systems accounting for only one product (monofunctional processes), allocation is direct. However, problems emerge when dealing with overall input/output data for a system which produces more than one product (multifunctional processes) or functions which influence more than one life cycle (e.g. open-loop recycling) (Feijoo et al. 2005).

Multifunctional processes are those processes whose function requires the concurrence of more than one process. They include production processes which give rise to more than one product, as well as waste treatment processes with more than one waste flow or energy generation (Ekvall & Finnveden 2001). In this type of systems, environmental burdens must be distributed among the different products or processes. With this purpose, inputs and outputs are allocated to the different products on the basis of procedures which must be clearly specified. Allocation procedures should capture the main features and relationships regarding inputs and outputs. The addition of the inputs and outputs allocated to a unit process shall equal the addition of the inputs and outputs prior to allocation.

Impact assessment

The objective of the life cycle impact assessment (LCIA) is to provide further information to evaluate the results of the life cycle inventory in order to better understand the environmental performance of a product system. This stage determines the relevance of the environmental impacts from the results of the previous phase. This step involves the association of inventory data with different environmental impact categories and their corresponding indicators.

LCIA includes the compilation of the resulting values for a set of indicators regarding different impact categories which, as a whole, show the LCIA profile for a certain product system.

The LCIA results present limitations concerning uncertainty because of the lack of space and time dimensions in the life cycle inventory results. Furthermore, there are no widely accepted methodologies which link inventory data and potential environmental impacts in a consistent and accurate way. Issues such as the selection, modelling and assessment of the impact categories add subjectivity to the LCIA stage.

The mandatory items in the LCIA phase comprise:

- Selection of impact categories, indicators and characterization models. This selection should include an exhaustive set of environmental issues related to the system under study, and should be in agreement with the defined goal and scope.
- Assignment of life cycle inventory results to the selected impact categories (classification).

- Calculation of the values for the category indicators (characterization). Characterization means the conversion of the life cycle inventory results to common units and the addition of the converted results belonging to the same impact category. This conversion uses characterization factors. The calculation output is the quantitative result of an indicator.

There are several LCIA options which can also be useful depending on the specific LCA goal and scope. They include:

- Normalization. It is the calculation of the magnitude of the indicators values related to the reference information. It is aimed to facilitate the understanding of the relative magnitude of each indicator.
- Weighting. It is the conversion and potential addition of the indicator results through the impact categories by means of numerical factors based on value judgments.
- Additional data quality analysis (gravity analysis, uncertainty analysis, sensitivity analysis).

Finally, it is important to distinguish the two different LCIA methodology groups according to their final objective:

- Environmental impact assessment methods (mid-point). These methods result in the definition of an environmental profile by means of the quantification of the environmental effect of the product on several categories (acidification, ozone layer depletion, etc.). Contrary to the second group, mid-point methods (also known as distance-to-target methods) evaluate the indirect/intermediate effects on the human being.
- Damage assessment methods (end-point). These methodologies evaluate the final effect of the environmental impact by identifying and determining the damage caused to the human being ant the natural systems.

Because of its use in this dissertation, one of the most common mid-point methods is here presented: the CML method published by the Centre of Environmental Science of the Leiden University (Heijungs et al. 1992). The CML guide (Guinée et al. 2001) provides a list of impact categories grouped in: (i) mandatory categories (categories used in most of the LCA studies), and (ii) other impact categories. Specifically, the mandatory impact categories are: acidification (Edwards & Hutton 1999), ozone layer depletion, abiotic resources depletion, global warming (Nakicenovic et al. 1998), eutrophication, human toxicity, ecotoxicity –fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity– (Huijbregts et al. 2001), and photochemical oxidant formation (UNECE 2003).

Interpretation

The interpretation of the life cycle results is the final stage of the LCA procedure. In this phase and according to the goal and scope defined for the LCA study, the results from the life cycle inventory analysis and the LCIA are summarized and discussed with the aim of identifying the relevant issues and drawing conclusions, recommendations and information for decision making.

2.3.2. Life Cycle Assessment for seafood

The first LCA studies on food were performed at the beginning of the nineties of the twentieth century, and since then, they have been used to answer questions about processing (identification of the most impact-contributing subsystems from an environmental perspective) as well as to compare food products or processes with the same function (Mattson & Sonesson 2003).

One of the sectors where LCA has been widely implemented is the agri-food sector, being a common requirement in marketing strategies. However, while LCA in agriculture is quite well established (Andersson 2000), the use of this tool to assess seafood production systems is a more recent phenomenon (Pelletier et al. 2007).

To date, the several researchers devoted to LCA of fisheries and aquaculture have evaluated a short number of species. Among the different studies, the following ones are highlighted:

- Norwegian cod fishing and salmon farming (Ellingsen & Aanondsen 2006).
- Danish fish products, especially focused on flatfish (Thrane 2006).
- Frozen fillets from cod fished in the Baltic Sea (Ziegler et al. 2003).
- Creeling and trawling of Norway lobster caught along the Swedish west coast (Ziegler & Valentinsson 2008).
- Production of rainbow trout in Finland (Grönroos et al. 2006).
- Trout farming in France (Papatryphon et al. 2004a, 2004b).

- Shrimp aquaculture in Thailand (Mungkung et al. 2006).
- Carnivorous finfish production (Aubin et al. 2006, 2009): rainbow trout in freshwater raceways in France, sea bass in sea cages in Greece, and turbot in an inland re-circulating system close to the seashore in France.
- Salmon culture in Canada (Ayer & Tyedmers 2009).
- Spanish tuna fisheries (Hospido & Tyedmers 2005) and canned tuna manufacture in Spain (Hospido et al. 2006).

As a whole, the conclusions drawn from these studies suggest the suitability of LCA to report environmental measures in both fishing and aquaculture. Specifically, the studies treating fisheries tend to identify the capture phase as the most contributing stage, mainly due to diesel demand. On the other hand, aquaculture studies usually stress the relevance of the farming stage because of the role played by feed and energy use.

Although there is a growing interest in the use of LCA methodology to improve the sustainability performance of seafood production and consumption systems, further efforts are needed (Pelletier et al. 2007; Ayer et al. 2009). This doctoral thesis contributes to widen the range of species studied under an LCA approach. Furthermore, this dissertation develops new trends in LCA of seafood such as the combined use of Data Envelopment Analysis (DEA) plus LCA, or the implementation of Carbon Footprinting (CF) schemes.

2.4. Carbon Footprinting

The increasing awareness of climate change as a global concern has led stakeholders to demand a standard procedure to measure and communicate greenhouse gas (GHG) emissions linked to consumer products. In this context, Carbon Footprinting (CF) has raised as an environmental tool not only for companies along the product chain but also for policy makers (Iribarren et al. 2010).

Carbon Footprinting (CF) involves the estimate of the overall amount of GHG emissions associated with a product (i.e., any good or service) along its supply chain, even including use and end-of-life recovery and disposal (EPLCA 2007). According to Carbon Trust et al. (2008), “the term ‘product carbon footprint’ refers to the GHG emissions of a product across its life cycle, from raw materials through production (or service provision), distribution, consumer use and disposal/recycling. It includes the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), together with families of gases including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)”.

Contrary to popular belief, CF is not a new topic. In fact, product carbon footprint is quantified using life cycle impact indicators for the global warming mid-point category. Hence, the carbon footprint could be understood just as a subset of the data covered by a more complete LCA. However, the use of carbon footprints for communication purposes questions the aptitude of the existing ISO standards to address the environmental impacts due to GHG emissions from products in a consistent and comprehensive way (SETAC 2008). Standardization efforts could be necessary to provide guidance for people interested in quantifying the carbon footprint of a product. Within this framework, several initiatives have arisen to meet the increasing market demand for climate relevant information along supply chains (Finkbeiner 2009).

This tool is further explained in Chapter 10, where the assessment of carbon footprints is discussed for the case of a common canned mussel product (Iribarren et al. 2010).

2.5. Data Envelopment Analysis

Data Envelopment Analysis (DEA) is a performance measurement methodology used to empirically quantify the comparative productive efficiency of multiple similar entities (Cooper et al. 2007). To carry out a DEA (Figure 2.5), data for inputs and outputs from the different entities must be known. From these data, DEA formulates and solves an optimization model which facilitates benchmarking the operational performance of each assessed entity. This benchmarking provides a basis for decreases in inputs per unit of output, usually resulting in an improved eco-efficiency. In this sense, DEA enables the discrimination of inefficient operating points, therefore promoting feasible technological improvements under the perspective of an efficient operational performance.

Therefore, DEA is a linear programming method to measure the efficiency of multiple Decision Making Units (DMUs) when the production process involves multiple inputs and outputs. A DMU is defined as the entity responsible for the conversion of inputs into outputs and whose performance is the object of assessment. DEA non-parametrically estimates the relative efficiency of a number of DMUs. Hence, DEA neither requires the user to set weights for each input and output nor demands the establishment of any functional form. Rather, DEA simply relies on the observed data for the inputs and outputs, and on a minimum of basic assumptions to solve an optimization model formulated for every DMU. The result for each DMU is an efficiency score and, for those DMU identified as inefficient, a target operating point.

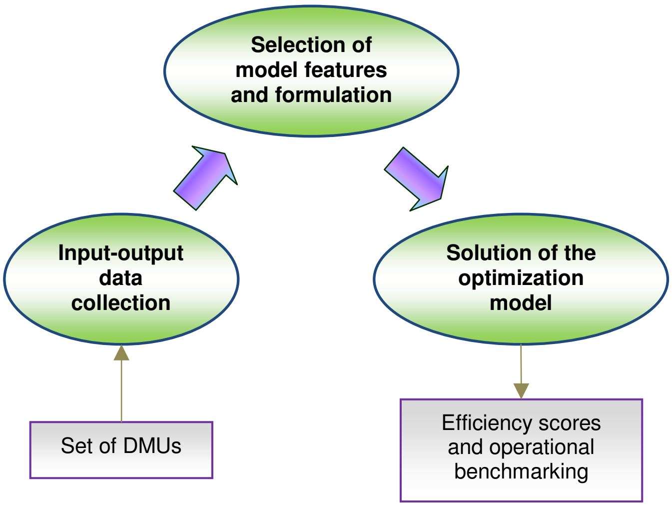

Figure 2.5. *Main steps in a DEA study*

DEA is further detailed in chapters 8 and 9, where the potentials of the combined application of LCA+DEA are discussed (Lozano et al. 2009, 2010; Vázquez-Rowe et al. 2010).

2.6. Objectives and structure of the dissertation

The goal of this doctoral thesis is to assess the environmental performance of the mussel and turbot aquaculture sectors in Galicia by adopting an LCA perspective. The identification of the corresponding environmental hot spots is pursued together with the proposal of some improvement potentials. In addition, further potentials in the use of LCA are discussed on the basis of some of the previous case studies. Specifically, the combined application of LCA and DEA, and the estimate of carbon footprints are matter of study.

As observed in Figure 2.6, the first two chapters (Section I) contextualize the study by introducing the aquaculture sector as well as the key tools used in this dissertation, that is, LCA, CF and DEA.

Section II is focused on the application of LCA to the mussel sector, including not only mussel aquaculture (Chapter 3), but also mussel processing (Chapter 4) and mussel waste treatment (Chapter 5). Hence, fresh, frozen and canned mussels are all environmentally assessed from an LCA approach.

Similarly, Section III aims to assess the turbot aquaculture by using LCA. The LCA of feed for aquaculture is carried out in Chapter 6 because of its relevance in the environmental performance of the turbot farms. Finally, Chapter 7 implements the LCA of aquafeed into the LCA case study of the turbot aquaculture.

On the other hand, Section IV uses some of the previous results in order to discuss the potentials of the use of other methodologies linked to LCA. Thus, chapters 8 and 9 present the combined use of LCA and DEA, and the application of the LCA+DEA methodology to the mussel culture case study. The environmental and operational performances of the mussel farming are discussed from two different perspectives: operational efficiency (Chapter 8) and environmental impact efficiency (Chapter 9). Furthermore, Chapter 10 shows how to assess the carbon footprint of a common canned mussel product according to an increasingly popular specification.

Finally, Section V (Chapter 11) summarizes the main conclusions of the previous chapters.

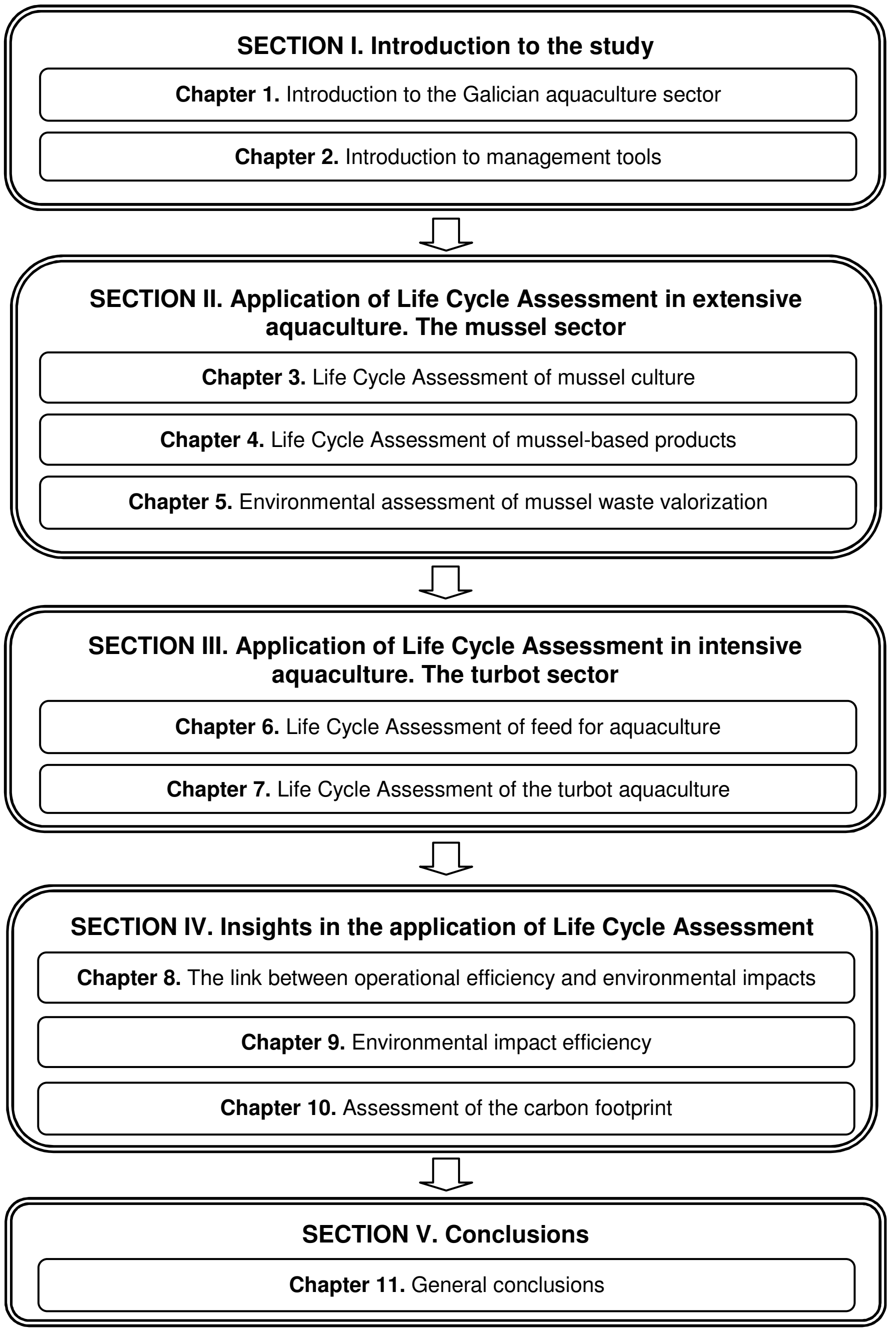

Figure 2.6. *Structure of the dissertation*

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SECTION II.

APPLICATION OF LIFE CYCLE ASSESSMENT IN EXTENSIVE AQUACULTURE. THE MUSSEL SECTOR

Chapter 3

Life Cycle Assessment of mussel culture[1]

Summary

The LCA of the mussel sector begins with Chapter 3, which deals with the culture phase. With this purpose, the main mussel production areas in Galicia were investigated. Inventory data came from interviews and surveys from a set of vessels accounting for the production of more than 7,000 tonnes of mussels cultured in rafts. In addition, physicochemical characterization of wastewater from the boats was performed.

Abiotic resources depletion, global warming, ecotoxicity, human toxicity, acidification, ozone layer depletion, photochemical oxidant formation and eutrophication were the impact categories evaluated. Characterization results for each of the categories revealed the importance of taking into account not only the operational issues, but also capital goods. Diesel use for the boat was found as the main contributor to potential environmental impacts, along with electricity and iron production linked to capital goods. Furthermore, an analysis with four different scenarios was carried out, highlighting the importance of studying capital goods in greater detail. Another analysis was performed to prove the lack of consensus when characterizing toxicity and ecotoxicity potentials.

Finally, mussel aquaculture was compared to mussel capture, finding that mussel aquaculture may present a higher potential environmental impact for farmed mussels due to a greater consumption of diesel and to the involvement of a number of operational inputs and outputs without correspondence in current data for mussel capture.

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[1] Iribarren, D., Moreira, M.T., Feijoo, G. (2010). “Life Cycle Assessment of mussel culture”. In: “Mussels: Anatomy, Habitat and Environmental Impact”, Nova Science Publishers, New York, USA (in press)

Index

3.1. Introduction

The expansion and intensification of aquaculture has raised a number of issues in terms of its negative impact on the environment. As previously mentioned in Chapter 1, mussels are the single largest cultured shellfish in Galicia (more than 200,000 tonnes per year), with a relevant impact on its economy (turnover of roughly 100,000,000 €) (Xunta de Galicia 2006). Galician cold waters and the regional geographic nature with characteristic rias provide fabulous aquaculture areas for farming mussels in floating structures called rafts.

Considering the great importance of the Galician mussel sector, this activity was considered for the evaluation of its environmental performance by LCA.

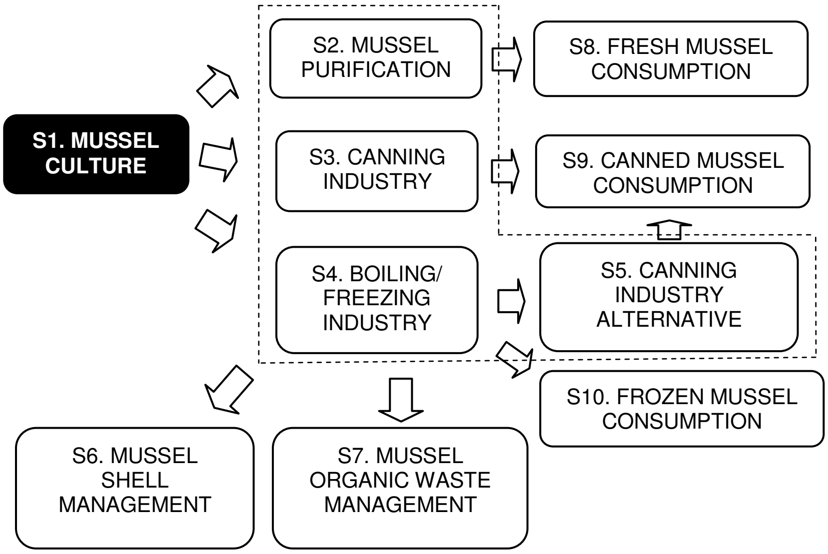

Figure 3.1. *The Spanish mussel sector. Dashed lines mean that the main inputs for systems S6 and S7 come from the mussel processing systems*

The Spanish mussel sector is divided into ten systems as shown in Figure 3.1:

- Mussel aquaculture in rafts (S1).
- Mussel purification in dispatch centres for the fresh-consumption market (S2).
- Mussel processing in canning factories to produce canned mussels (S3).

- Mussel processing in cooking plants to produce either frozen (S4) or canned mussels (S4 and further processing in S5).
- Final consumption of fresh (S8), canned (S9) and frozen (S10) mussels.
- Valorization of mussel shell and debris from processing factories to produce calcium carbonate (S6).
- Treatment of the mussel organic remains from processing plants (S7).

This chapter is focused on the evaluation of the environmental impacts associated with mussel culture in traditional rafts in Galicia.

3.2. Methods

The main objective of this chapter is to evaluate the potential environmental impacts linked to mussel (*Mytilus galloprovincialis*) aquaculture. To achieve this goal, inventory data from interviews and surveys from a representative sample of 22 vessels accounting for the production of more than 7,000 tonnes of farmed mussels were collected. The identification of the activities with a significant environmental impact will make it possible to propose a framework for alternatives which leads to a better environmental performance.

3.2.1. System boundaries

Figure 3.2 presents a diagram of the system under study (S1). All the activities performed in the raft were included, from seed collection to the packaging prior to the dispatch of the cultured mussels. Furthermore, construction, operation and maintenance of the raft as well as of the auxiliary cultivation boats were also considered. The term auxiliary boat is used to distinguish boats used for aquaculture purposes from regular fishing vessels.

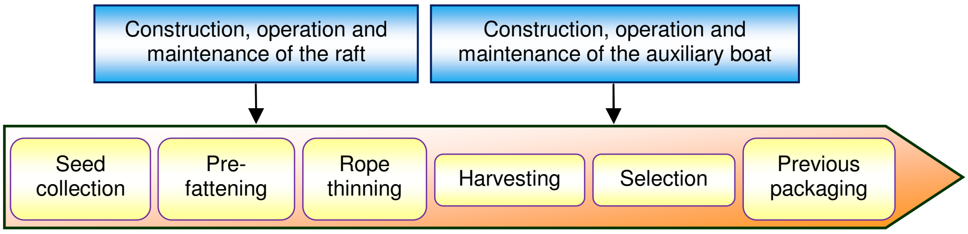

Figure 3.2. *System under study: mussel culture (S1)*

The system boundaries for the LCA of mussel cultivation included all the abovementioned activities as a whole, then demanding one thorough inventory. Figure 3.3 shows the process flow diagram for mussel culture.

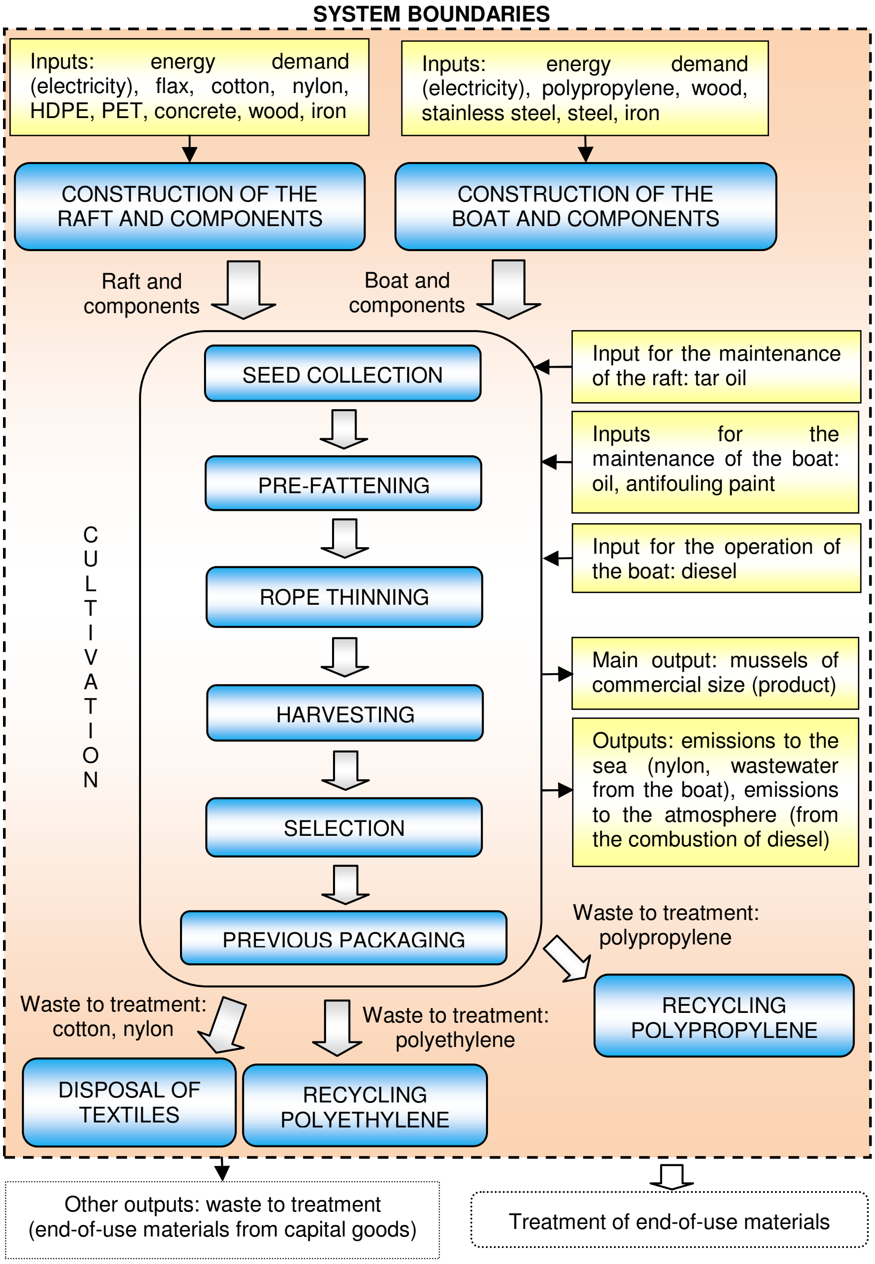

Figure 3.3. *Process flow diagram for mussel aquaculture*

As shown in Figure 3.3, some aspects concerning capital goods were included. Capital goods mean goods, such as machinery and equipment, used in the life cycle of products. Therefore, the consumption of inputs for the construction of the boat, the raft and their components were considered; however, the treatment of end-of-use materials from capital goods was excluded because of the lack of reliable information. Regarding capital goods, the following items were studied: (i) overall energy demand (electricity); (ii) textile materials (flax, cotton, nylon) for ropes, thin nets and yarns; (iii) polypropylene (PP) for big-bags; (iv) high density polyethylene (HDPE) for plastic pegs; (v) PET for floats; (vi) concrete for anchoring blocks; (vii) wood for the raft and the auxiliary boat; (viii) stainless steel for machinery (de-clumping machine, re-tubing machine, basket, etc.); (ix) steel for machinery (hydraulic crane); and (x) iron for floats, shackle chain and engines.

3.2.2. Functional unit

The annual production of a raft was chosen as FU: 89.74 t/raft (calculated as the average value from questionnaires). This value represents the annual mussel production of a conventional raft and corrects the average value of 50 t/raft often linked to these culture systems by other sources (AMEGROVE 2007; Pedramol 2007).

3.2.3. Data acquisition

According to official data from the regional government, the number of vessels operating in aquaculture-related activities in Galicia was 1,096 in 2007 (Plataforma Tecnolóxica 2007). More than 85% were located in the southwest. Therefore, the Ria de Arousa was selected as the most representative geographical area for the study of mussel culture, accounting for 71% of the aquaculture fleet. Further details about location are provided in Figure 3.4.

A questionnaire was prepared to collect the necessary data for the different processes involved. This questionnaire was delivered to the skippers of the auxiliary boats in charge of 80 rafts and comprised a wide range of structural and operational aspects (dimensions; hull material; power of main and auxiliary engines; annual consumption of diesel, oil and antifouling paint; average disposal of wastewater; etc.) as well as aspects related to the raft (construction material, dimensions, life span, number/material/dimensions of the floats, anchoring system, annual consumption of tar oil, etc.).

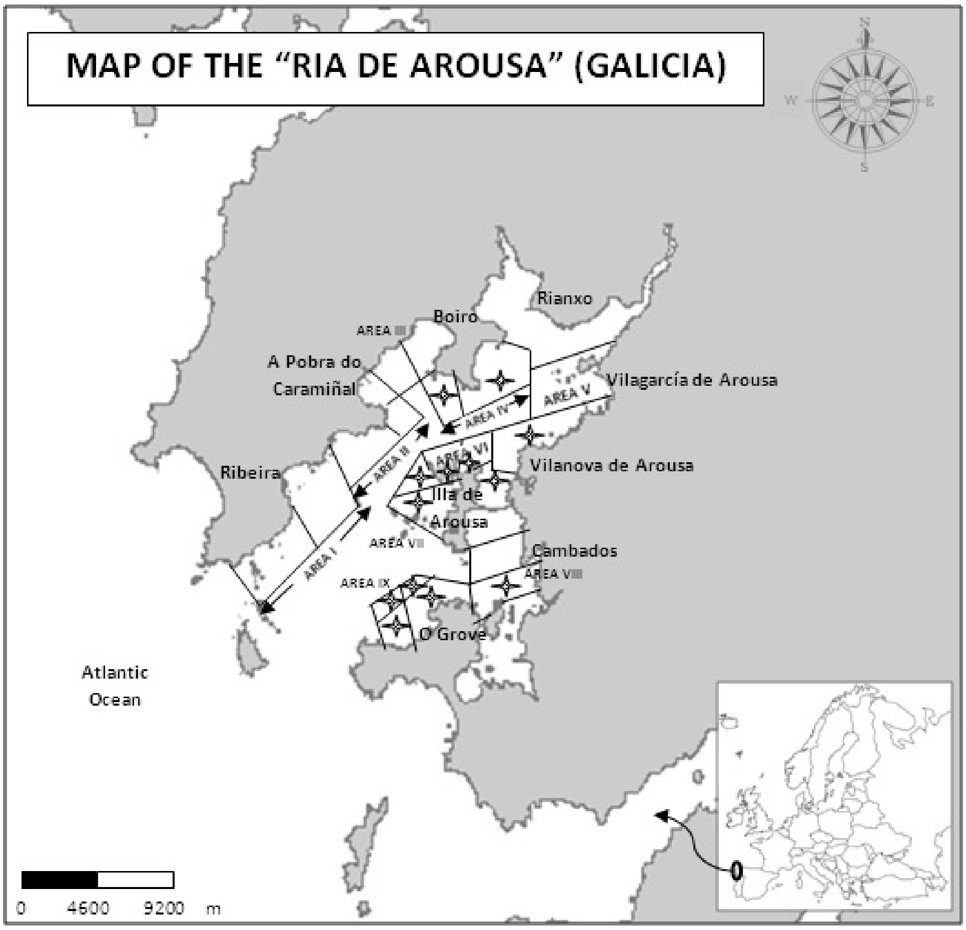

Figure 3.4. *Areas of study for mussel culture in rafts. The star symbols indicate the studied parks*

In order to evaluate emissions to the sea, wastewater samples collected from three boats were analytically measured. Samples were taken during a one-year period, taking into account seasonal variations in mussel cultivation, which inherently affect vessel operation. Standard methods (APHA 1995) were used in order to value the main physicochemical parameters: Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD_5), Total Solids, Total Volatile Solids, Total Suspended Solids, Total Volatile Suspended Solids, chloride, Total Organic Carbon (TOC), Total Kjeldahl Nitrogen (TKN), fats and oils, etc. In addition, metal content (Cl, Br, Rb, Sr, K, Fe, Ca) was determined using X-ray fluorescence. Furthermore, the concentrations of 16 polycyclic aromatic hydrocarbons (PAHs) including acenaphtene, acenaphthylene, anthracene, benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(g,h,i)perylene, chrysene, dibenzo(a,h)anthracene, phenanthrene, fluoranthene, fluorene, indenopyrene, naphthalene and pyrene were ion-chromatographically determined. Most of these PAHs were found not to reach the detection limit but chrysene, phenanthrene and fluoranthene did. Therefore, they were included as part of the life cycle inventory for mussel culture.

The information provided by the survey was completed with data from different companies, including data from engines (Caterpillar 2007), specific equipment for mussel culture (Talleres Aguin 2007), hydraulic cranes (Industrias Guerra 2007) and specific products for myticulture (JJ Chicolino 2007). To a lesser extent, reference values from bibliographic sources were used (Cáceres-Martínez et al. 1994; Pérez-Camacho et al. 1995; García et al. 2000; Troell et al. 2004).

The energy demand for capital goods was considered by using the electricity production mix for Spain as presented in the ecoinvent database (Dones et al. 2007).

Additionally, allocation may be necessary when a process yields more than one product. In this case, the mussel seed was taken as an intermediate product. Nevertheless, unlike mussel capture, mussel aquaculture involves just one final product: commercial size mussels. Then allocation is not necessary and 100% of the environmental burdens shall be imposed to the main product.

Finally, life times for capital goods were taken into account. According to the questionnaires for this case study, a life time of 12.5 years was assumed for textile materials and plastic pegs as well as 19.5 years for floats, anchoring blocks, chain and raft wood, 5 years for big-bags, and nearly 32 years for boat wood. Life times for machinery ranged from 10 to 25 years depending on each machine (Tirado & Macias 2006).

3.2.4. Life cycle inventory

As stated before, the questionnaire was filled out by the skippers of auxiliary boats in charge of 80 rafts. The average annual production per raft resulted in 89.74 tonnes of mussels. Therefore, the total production evaluated was around 7,180 tonnes.

Mussel culture in Galicia presents very well-defined characteristics inside a particular legal framework; therefore, a set of standard values for mussel farming in conventional rafts was established in order to propose a model for the raft (Table 3.1) and the auxiliary boat (Table 3.2). Some of the inventoried elements can be observed in Figure 3.5.

On the other hand, emissions to the ocean were considered using real data from laboratory measures and the average value for the loss of ropes (nylon) from questionnaires. No estimates involving other items were included. Consequently, for the purpose of considering wastewater from auxiliary boats, analytical measurements of the main corresponding parameters were needed; they are detailed in Table 3.3.

Table 3.1. *Conventional values for auxiliary boats used in mussel aquaculture*

Parameter	Value	Standard deviation	Units
Hull material	Wood	-	-
Length	16.68	2.34	m
Width	5.38	0.99	m
Life span	31.88	5.74	year
Main engine power	209.65	89.03	hp
Auxiliary engine power	53.06	29.70	hp
Crew	2.88	1.05	people
Number of attended rafts	3.65	1.84	rafts
Distance to cultivation site	2.49	1.65	miles
Annual consumption of diesel	5,225.00	3,100.22	l/year
Annual consumption of oil	87.34	58.56	l/year
Annual consumption of paint	60.00	36.25	l/year
Time for maintenance and repairs[a]	26.67	9.19	d/year
Monthly wastewater	30.83	18.28	l/month

[a] The auxiliary boat works an average of 180 days per year

Table 3.2. *Conventional values for rafts used in mussel aquaculture*

Parameter	Value	Standard deviation	Units
Material	Wood	-	-
Length	26.55	1.06	m
Width	20.14	0.64	m
Number of floats	5.90	0.72	floats
Material of the floats	Iron[a]	-	-
Floats length	2.17	0.07	m
Floats diameter	3.73	0.54	m
Weight of the concrete anchoring block	18.91	6.93	t
Life span	19.50	5.60	years
Annual consumption of tar oil	109.56	68.65	l/year
Rope length[b]	11.72	0.64	m
Rope material	Nylon	-	-
Material of the mussel pegs[c]	Plastic (HDPE)	-	-
Annual consumption of cotton[d]	19.14	17.04	boxes/year

[a] Iron covered with polyester

[b] The length for collector ropes (for seed) is 5.00 m

[c] Each peg is placed through the rope with a separation of 40 cm

[d] Each box contains 500 m of cotton

Table 3.3. *Analytical data of wastewater from auxiliary boats for mussel farming*

Parameter	Value	Parameter	Value
pH	7.28 ± 0.48	Total Volatile Suspended Solids (g/l)	0.18 ± 0.15
Total COD (g O_2/l)	0.65 ± 0.31	Chloride (g/l)	24.66 ± 3.86
Soluble COD (g O_2/l)	0.43 ± 0.28	TOC (g C/l)	0.05 ± 0.07
BOD_5 (g O_2/l)	0.04 ± 0.06	Inorganic Carbon (g C/l)	0.04 ± 0.01
Total Solids (g/l)	44.65 ± 10.75	Total Carbon (g C/l)	0.09 ± 0.08
Total Suspended Solids (g/l)	0.22 ± 0.16	Ammoniacal nitrogen (mg N/l)	0.58 ± 1.37
Total Volatile Solids (g/l)	11.12 ± 8.50	Organic Nitrogen (mg N/l)	5.57 ± 4.37

Table 3.3. *Analytical data of wastewater from auxiliary boats for mussel farming (cont.)*

Parameter	Value	Parameter	Value
Fats (mg/l)	0.95 ± 0.56	Calcium (%)	0.02 ± 0.02
Chlorine (%)	0.74 ± 1.02	Iron (mg/l)	9.33 ± 14.33
Bromine (mg/l)	74.52 ± 16.72	Chrysene (µg/l)	0.023 ± 0.01
Rubidium (mg/l)	0.87 ± 0.78	Phenanthrene (µg/l)	0.019 ± 0.01
Strontium (mg/l)	7.52 ± 0.77	Fluoranthene (µg/l)	0.014 ± 0.01
Potassium (%)	0.03 ± 0.02		

Figure 3.5. *Some inventoried elements: (1) hydraulic crane and basket, (2) rope with plastic pegs, (3) shackle chain, (4) grading table, (5) de-clumping machine, re-tubing machine and big-bag, (6) engine*

Considering all the available information, the life cycle inventory for mussel culture is presented in Table 3.4. Although the FU corresponds to the annual production of a raft, Table 3.4 is presented for the production of 1 kg of farmed mussels of commercial size in order to make the reading easier. The main input from nature corresponds to mussel seeds, which are obtained from coastal rocky areas where mussel farmers collect the seeds by means of scrapers (Cáceres-Martínez et al. 1994), and also from collector ropes and netting strips (Tirado & Macias 2006). The other main inputs gathered in the inventory table come from the technosphere, emphasizing the input of Diesel B for use in the auxiliary boat, whose value is in agreement with bibliographic sources (Troell et al. 2004). Another important input to consider is the amount of wood required, which is also in line with other data published elsewhere (García et al. 2000).

Table 3.4. *Life cycle inventory for mussel culture in traditional rafts*

INPUTS					
From the technosphere			**From the environment**		
Materials and fuels			**Raw materials**		
1. Chemicals and other materials			1. Seeds from rocky shoreline		
Iron	13.03	g	Mussel seed	5.85	g
Antifouling paint	0.17	g	Use of rocky shoreline	$5.16\cdot10^{-8}$	ha
Stainless steel	0.08	g	2. Seeds from collector ropes		
Other steels	0.19	g	Mussel seed	9.05	g
Nylon	3.55	g	3. Seeds from netting strips		
HDPE	0.32	g	Mussel seed	1.81	g
PET	0.02	g	Total mussel seed	16.71	g
Concrete	10.81	g	4. Use of sea surface	59.56	cm^2
Cotton	0.27	g			
Acetate rayon	9.47	mg			
Flax	6.69	mg			
Polypropylene (PP)	0.33	mg			
Tar oil	1.22	ml			
Oil C_{15}-C_{50}	0.27	ml			
2. Wood					
Pine and oak	1.84	g			
Eucalyptus	36.87	g			
Ash tree	0.01	mg			
Total Wood	38.71	g			
3. Diesel B	15.96	ml			
Energy					
1. Infrastructure and equipments	2.67	MJ			

Table 3.4. *Life cycle inventory for mussel culture in traditional rafts (cont.)*

OUTPUTS					
To the technosphere			**To the environment: emissions to the ocean**		
Final products and intermediate products			1. Wastewater from auxiliary boats		
1. Mussel of commercial size	1.00	kg	Total COD	0.37	mg O_2
2. Mussel seed (intermediate product)	16.71	g	BOD_5	0.02	mg O_2
Waste to treatment			Dissolved solids	25.11	mg
1. Polypropylene (PP)	15.24	g	Suspended solids	0.12	mg
2. HDPE	0.04	g	Chloride	19.94	mg
3. Cotton	0.06	g	TOC	0.03	mg C
4. Nylon	0.64	g	Chlorine	4.18	mg
To the environment: emissions to air			Bromine	0.04	mg
1. Carbon dioxide	43.10	g	Potassium	0.17	mg
2. Methane	3.99	mg	Calcium	0.11	mg
3. Dinitrogen monoxide	1.09	mg	Organic nitrogen	3.34	µg N
4. Sulphur dioxide	39.91	mg	Fats	0.55	µg
5. Carbon monoxide	100.58	mg	Rubidium	0.45	µg
6. Nitrogen oxides	766.30	mg	Strontium	4.45	µg
7. NMVOC	31.93	mg	Iron	5.57	µg
			Chrysene	0.01	ng
			Phenanthrene	0.01	ng
			Fluoranthene	0.01	ng
			2. Nylon	0.12	g

3.3. Results

SimaPro 7 was the software used for the computational implementation of the inventory (Goedkoop et al. 2008). The ecoinvent database was chosen for background processes (Frischknecht et al. 2007a), while bibliographic data were used to make the inventory of flax yarn production (Turunen & van der Werf 2006). Classification and characterization following ISO guidelines were performed to assess the potential environmental impact of inputs and outputs from the LCI (ISO 2006). An attributional LCA for mussel culture was made using the CML mid-point method, which results in the definition of an environmental profile for the assessed product by means of the quantification of the environmental effect on different categories. The following impact categories were considered: acidification potential (AP), ozone layer depletion potential (ODP), abiotic depletion potential (ADP), global warming potential (GWP), eutrophication potential (EP), photochemical oxidant formation potential (POFP), fresh water aquatic ecotoxicity potential (FETP), marine aquatic ecotoxicity potential (METP), terrestrial ecotoxicity potential (TETP), and human toxicity potential (HTP). This set of categories is common in LCA for seafood (Pelletier et al. 2007).

When assessing the potential environmental impacts of myticulture, it is advisable to distinguish contributions linked to operation from those related to capital goods (Frischknecht et al. 2007b). Taking this into account, Table 3.5 shows the characterization results for mussel culture.

Table 3.5. *Environmental characterization for mussel culture in traditional rafts using CML 2 baseline 2000 method*

Impact category	**Unit**	**Value**		
		Capital goods	**Operation**	**Total**
Abiotic depletion	kg Sb eq	28.67	27.37	56.03
Global warming	kg CO_2 eq	35,862.85	2,553.03	38,415.88
Ozone layer depletion	kg CFC-11 eq	0.0017	0.0062	0.0079
Human toxicity	kg 1,4-DB eq	11,786.38	1,646.11	13,432.49
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	3,761.44	116.90	3,878.34
Marine aquatic ecotoxicity	kg 1,4-DB eq	49,951,170.96	533,774.13	50,484,945.09
Terrestrial ecotoxicity	kg 1,4-DB eq	81.45	-2.69	78.76
Photochemical oxidant formation	kg C_2H_2 eq	21.38	0.13	21.50
Acidification	kg SO_2 eq	563.65	20.76	584.41
Eutrophication	kg PO_4^{3-} eq	24.46	7.85	32.30

The term capital goods involves the consumption of energy, iron, concrete, textile materials, plastics, steel and wood for the construction of machinery and equipment used in mussel farming, but cutting off the treatment of these materials after their use.

On the other hand, the term operation stands for (i) diesel use for the operation of the boat, (ii) the use of oil and antifouling paint for the maintenance of the boat, (iii) tar oil use for the maintenance of the raft, (iv) treatment of solid wastes from operation, and (v) wastewater from boats. This latter was considered the only direct emission to the sea, and its analytical study provided real (non-estimated) values for the associated pollution. No estimates concerning other emissions to the sea were included, meaning that the release of non-ferrous metals related to the use of antifouling paint was excluded on the rationale of a lack of agreement between toxicity factors and the state of the oceans, which are deficient in this type of metals (Hospido 2005). With regard to operation in mussel aquaculture, it should be emphasized that there is neither electricity consumption nor refrigeration involved within this operational chain.

Figure 3.6 clearly shows the contribution of operation and capital goods to the environmental impact categories, demonstrating the importance of considering capital goods as an impact source within mussel aquaculture. The extensive and non-continental nature of mussel farming in Spain put forward this result as known for agricultural products according to the recommendations of Frischknecht et al. (2007b).

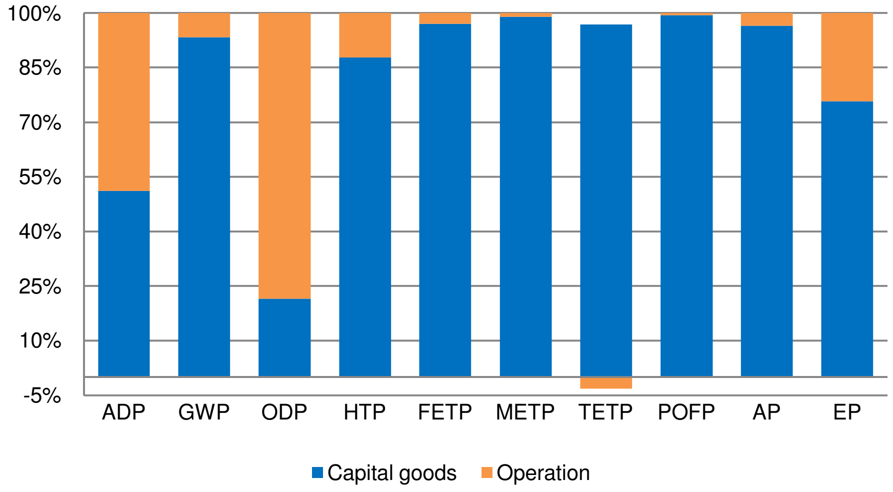

Figure 3.6. *Contribution of operation and capital goods to the potential environmental impacts linked to mussel culture*

As shown in Figure 3.6, capital goods established themselves as the main origin of the potential environmental impacts related to the following categories: AP, EP, POFP, GWP, HTP and the three ecotoxicity categories (FETP, METP and TETP).

Regarding ADP, a similar contribution for both operation and capital goods was observed. However, the main contribution to ODP came from operation, which accounted for roughly 80% of the total potential impact for this category, while the remaining 20% was linked to capital goods.

Once the potential contribution of capital goods and operational issues was compared for the different categories, the next step consisted of the identification of the main processes contributing to potential environmental impacts in mussel culture. This step determines the usefulness of LCA as a decision supporting tool, and its results are summarized in Figure 3.7, where the potential contributions to each of the impact categories are shown for the six processes identified as the main contributors.

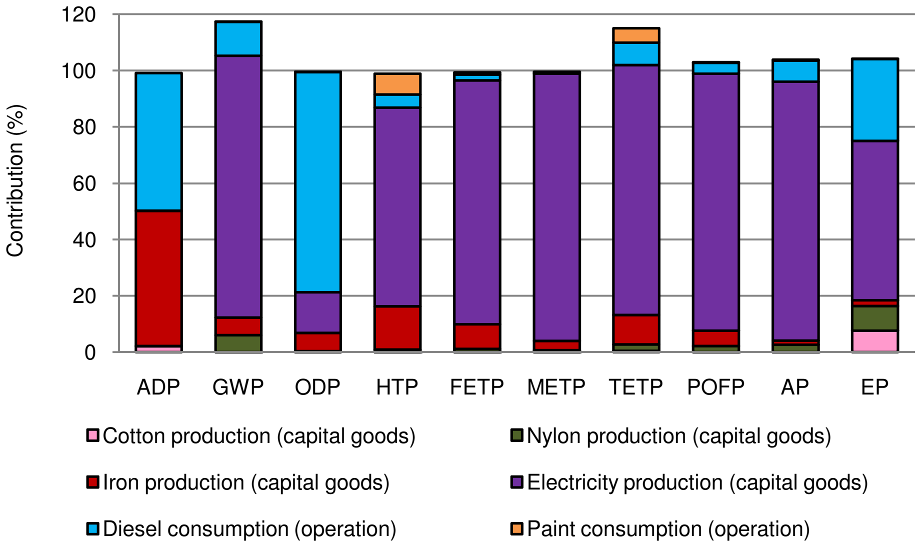

Figure 3.7. *Process contribution for mussel farming in rafts*

As captured in Figure 3.7, three processes stood out as the main sources of the potential environmental impacts: electricity production for capital goods, diesel use in boat operation and, to a lesser extent, iron use for capital goods.

Electricity production corresponds to the electricity production mix for Spain. This process prevailed for GWP (contribution of more than 90% to the potential impact for this category), POFP (91%), AP (92%), and EP (57%), as well as for the four toxicity and ecotoxicity categories (71% for HTP, 87% for FETP, 95% for METP, and 89% for TETP). Moreover, electricity production for capital goods accounted for 14% of the potential impact for ODP.

Diesel use included diesel production as well as its combustion for boat operation. This process arose as the main potential source of impact for ADP (potential contribution of 49% to this impact category) and ODP (78%). It also entailed a relevant contribution to the potential environmental impact for EP (29%), GWP (12%) and TETP (8%).

Iron use for capital goods also played a role in the environmental characterization of mussel farming. This is mainly due to the large weight of floats and shackle chains for rafts even though their lifetimes have been taken into account. Thus, this process significantly contributed to ADP with a percentage of 48% of the impact for this category, also involving lower percentages for GWP (6%), ODP (6%) and POFP (5%). Furthermore, toxicity and ecotoxicity categories were also affected by this process (15% for HTP, 9% for FETP, 3% for METP and 10% for TETP).

To a lesser extent, other processes contributed to the potential environmental impacts. For example, nylon production (mainly related to the use of ropes for mussel farming) accounted for a contribution of 9% to EP, 6% to GWP, and 2% to POFP, AP and TETP. Other examples are paint production for the maintenance of the boat (contribution of 7% to HTP and 5% to TETP) or cotton production (contribution of 8% to EP and 2% to ADP).

3.4. Discussion and identification of improvement potentials

3.4.1. Toxicity and ecotoxicity potentials

The toxicity and ecotoxicity values obtained from characterization strongly depend on the selected method (Renou et al. 2008). In order to study this dependence, the EDIP 2003 method was used, obtaining new values to characterize toxicity and ecotoxicity potentials. Thus, Table 3.6 compares these values with those corresponding to CML 2000. The following conclusions were drawn:

- The lump sum of the values for the three EDIP 2003 categories linked to human toxicity accounted for 97.93% of the total toxicity impact; whereas, if CML 2000 is used, then the value for the human toxicity potential only involved 0.03% of the total toxicity impact.

- If EDIP 2003 is used, the sum of the values for the two different categories related to water ecotoxicity accounted for only 2.06% of the total toxicity impact; while the value of the sum of the two CML 2000 categories associated with water ecotoxicity meant 99.97%.
- Finally, the value for soil (terrestrial) ecotoxicity potential accounted for $1.66 \cdot 10^{-3}$% of the total toxicity impact when using EDIP 2003 and, similarly, for $1.46 \cdot 10^{-4}$% if CML 2000 is used.

According to the two first conclusions, a lack of consensus was proved when characterizing toxicity and ecotoxicity potentials. Nevertheless, both methods led to the same main contributor: electricity production to satisfy the energy demand for capital goods.

Table 3.6. *Toxicity and ecotoxicity comparison using two different methods*

CML 2 baseline 2000			
HTP	**FETP**	**METP**	**TETP**
(kg 1,4-DB eq)			
13,432.49	3,878.34	50,484,945.08	78.76

EDIP 2003 V1.01					
ETWC	**ETWA**	**ETSC**	**HTA**	**HTW**	**HTS**
(m^3)					
6,430,372.11	2,341,658.90	7,069.15	415,816,565.28	320,533.93	3,610.16

ETWC: ecotoxicity water chronic
HTA: human toxicity air
ETWA: ecotoxicity water acute
HTW: human toxicity water
ETSC: ecotoxicity soil chronic
HTS: human toxicity soil

3.4.2. Eutrophication potential

When studying mussel farming, EP also becomes a controversial impact category. In this respect, it has been suggested that mussels (filter feeders) can act as a buffer against eutrophication processes since they mean a top down control on the phytoplankton biomass and sequester nutrients, which would be removed if mussels were harvested (Nakamura & Kerciku 2000; Cloern 2001). However, Nizzoli et al. (2005) estimated the global effects of suspended mussel (*Mytilus galloprovincialis*) farming on oxygen and nutrient dynamics. This study found ratios between particulate nutrient consumption and net dissolved nutrient regeneration rates of 1.1 for nitrogen and 2.5 for phosphorous. Nevertheless, their results question the belief that dense populations of mussels act as a buffer against eutrophication problems since, whilst it was true that the mussel ropes exerted an intense grazing pressure on the phytoplankton, the ingested organic nutrients were rapidly recycled back to the water column by the mussel ropes and the underlying sediments, where they would stimulate further phytoplankton growth. Thus, the net effect of mussels may be to increase phytoplankton turnover and productivity, rather than to decrease phytoplankton biomass. Consequently, in this LCA of mussel farming, it was decided not to perform any correction factor regarding the characterization value for EP, which would lead to an EP value lower than that gathered in Table 3.5.

3.4.3. Improvement potentials

Characterization results are very useful when approaching improvement actions in the myticulture field. In this sense, LCA for mussel culture led to focus the identification of improvement potentials not only on operational issues but also on capital goods. However, specific improvement actions on capital goods are difficult to identify because of the prevalence of electricity production as the main contributor to the different impact categories.

Related to energy consumption, mussel cultivation is not considered to be an activity with high energy consumption as compared to the cultivation of other species such as shrimp or salmon (Troell et al. 2004), especially regarding operational activities. Nonetheless, according to the previous results, it seems evident that improvement actions concerning operation should be centred on the minimization of diesel consumption in the auxiliary boat, which would lead to a significant improvement for the environmental indicators studied. Efforts should be made with the objective of reducing the diesel demand for operation in auxiliary boats: use of fuels with higher energy efficiency, sustainable planning and logistic organization of boat route up to the rafts, etc.

Regarding capital goods, it would be advisable to act on the corresponding energy demands. However, the estimated term energy demand for capital goods involves all the capital goods for mussel farming and then actions on this term become difficult. On the contrary, this obstacle is not found when dealing with the minimization of iron consumption, since improvement potentials affect a limited set of capital goods: engines, floats, chains and shackles. For these improvement purposes, there is a wide range of alternatives including technological innovation (such as the use of new materials).

3.4.4. Electricity demand for capital goods

According to the environmental characterization results, electricity production for capital goods was found as one of the main contributors to the different impact categories. However, the value of the electricity demand for capital goods means a rough estimate and it should be more accurate, which could be achieved by inventorying in greater detail the different capital goods involved in mussel culture. Since this possibility is out of the scope of this dissertation, an additional analysis was carried out according to four different scenarios with the aim of assessing the relevance associated with the uncertainty in the value of the electricity demand:

- Scenario 0: case study (no action).
- Scenario 1: reduction of 10% for the overall energy (electricity) demand for capital goods.
- Scenario 2: reduction of 25%.
- Scenario 3: reduction of 50%.

Figure 3.8 shows that as the overall energy demand for capital goods was decreased, a gradual reduction in characterization values was observed. This reduction was clear for GWP, AP, METP, HTP, TETP, POFP, FETP and EP. On the other hand, there was no influence over ADP, and the influence was minimal for ODP.

These observations stress the importance of studying capital goods in greater detail. The performance of further analyses involving scenarios with different models for electricity production was not considered necessary, since the electricity production mix for Spain is assumed to be the most accurate approach. In fact, the uncertainty is primarily focused on the value itself, not on the electricity mix.

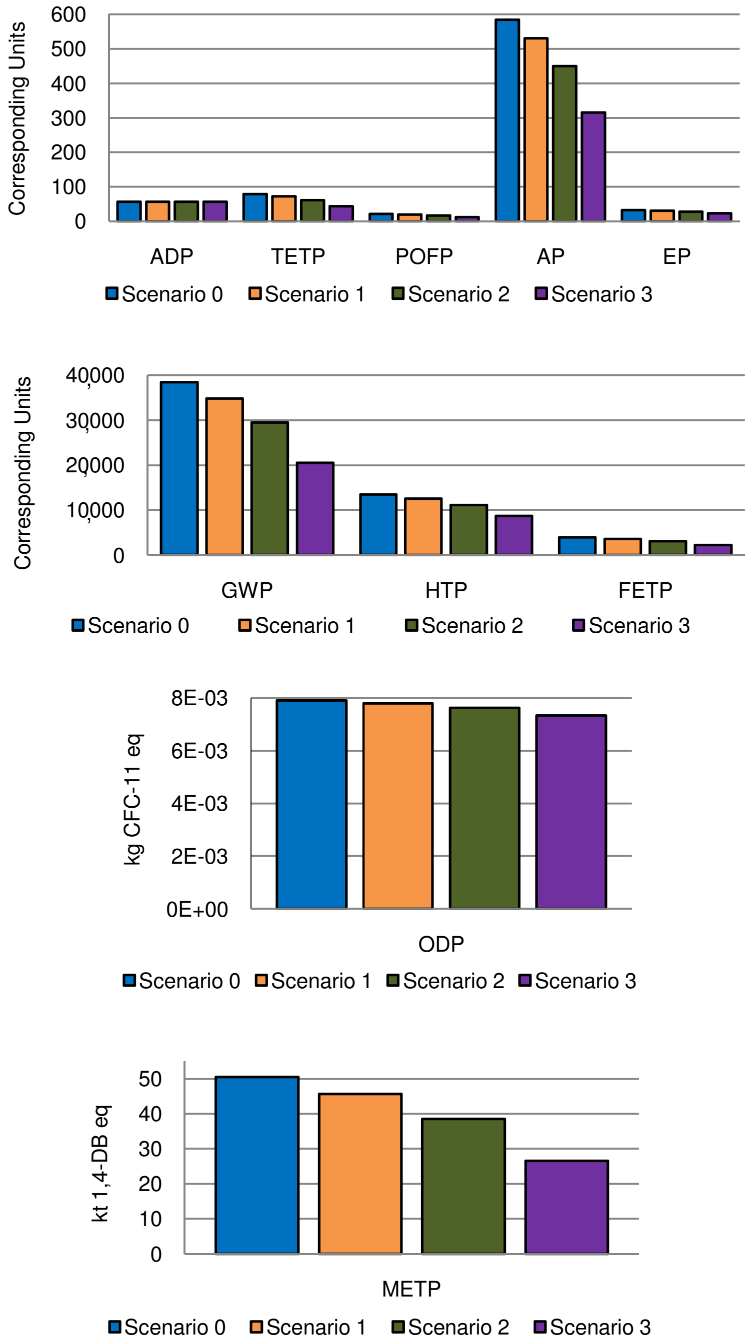

Figure 3.8. *Analysis for the relevance of the energy value used in capital goods*

3.4.5. Mussel capture

Thrane (2004) studied the environmental impacts for several Danish products, including mussels obtained from capture. The comparison between mussel aquaculture and capture was then possible in terms of a comparative LCA, but only including the operational activities, given that input data for mussel capture as implemented into the LCA food data base (Nielsen et al. 2003) just consider the diesel input for vessel operation.

In Table 3.7, the characterization ratios for mussel aquaculture versus mussel capture are shown for each of the environmental impact categories. For every category, the ratio of aquaculture to capture is clearly greater than one. Therefore, a higher potential environmental impact for farmed mussels is observed. This is related mainly to the involvement of a number of operational inputs and outputs without correspondence in current data for mussel capture. Furthermore, mussel aquaculture entails a greater consumption of diesel: 0.016 l diesel/kg of farmed mussels versus 0.012 l diesel/kg of captured mussels. Finally, it should be pointed out that this is a rough comparison which omits the difference in production capacity between mussel aquaculture and capture.

Table 3.7. *Environmental comparison between mussel aquaculture and mussel capture*

Impact category	Ratio aquaculture/capture
Abiotic depletion	1.50
Global warming	1.38
Ozone layer depletion	1.33
Human toxicity	2.62
Fresh water aquatic ecotoxicity	1.56
Marine aquatic ecotoxicity	1.43
Terrestrial ecotoxicity	3.56
Photochemical oxidant formation	1.50
Acidification	1.40
Eutrophication	1.35

3.5. Conclusions, recommendations and perspectives

This is the first time that LCA has been used to assess the environmental performance of mussel aquaculture in traditional rafts. Models for rafts and auxiliary boats for mussel culture were presented, and a detailed inventory was made from data provided by different skippers from the main production areas. The current availability of such operational and environmental information is one of the main targets attained; actually, it is imperative where an LCA study is performed.

In order to identify the environmental hot spots of mussel culture, different impact categories were studied. The potential environmental impacts linked to capital goods were distinguished from those related to operation. As a result, potential improvements were proposed, which led to emphasize the importance of minimizing energy demand and iron use for capital goods; in addition, with regard to operation, the minimization of diesel consumption in auxiliary boats was primarily suggested.

On the other hand, the rough environmental comparison between mussel aquaculture and capture showed a potentially higher environmental impact for mussel culture due to greater diesel consumption for vessel operation and to the inclusion of additional inputs and outputs.

Regarding mussel farming, further studies with inventories for individual equipments are recommended, as well as comparative LCA case studies which implement corrective actions. In particular, as concluded according to the analysis performed for the energy value, new efforts are needed in order to get a more accurate value for the energy demand for capital goods.

Furthermore, the implementation of biological aspects should also be explored in further research, especially with the purpose of specifying toxicity, ecotoxicity and eutrophication potentials, although, as stated before, there are important difficulties in order to faithfully characterize these categories with the different methods. Finally, further studies should be addressed to environmentally assess new capital goods options such as submerged platforms, which have arisen as an alternative for the traditional rafts.

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Chapter 4

Life Cycle Assessment of mussel-based products[1,2]

Summary

Mussels as a commercial product involve a range of activities which can be included within four different sub-sectors: culture, dispatch centres, canning factories and cooking plants. This chapter deals with the environmental evaluation of three different mussel products which correspond with the main mussel processing alternatives.

The use of exhaustive inventories led to the subsequent environmental characterization of the mussel sector in terms of the contribution observed for each of the sub-sectors. In this sense, the sub-sector associated with dispatch centres presented the largest contributions to the potential environmental impacts, clearly ahead of mussel farming. On the other hand, the sub-sectors of mussel cooking plants and canning factories showed a much lower contribution to the overall potential environmental impacts. Several improvement potentials were identified from the characterization results; in this sense, the minimization of the electric energy consumption in dispatch centres is highlighted.

Moreover, according to the results from the comparative LCA among the three main commercial mussel products –fresh mussels, canned mussels and frozen mussels–, fresh mussels were found to have the least favourable environmental profile.

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[1] Iribarren, D., Moreira, M.T., Feijoo, G. (2010). “Life Cycle Assessment of fresh and canned mussel processing and consumption in Galicia (NW Spain)”. Resour Conserv Recy (in review)

[2] Iribarren, D., Moreira, M.T., Feijoo, G. (2010). “Revisiting the Life Cycle Assessment of mussels from a sectorial perspective”. J Clean Prod 18, 101-111

Index

4.1. Introduction

Mussels are becoming a very popular food within the current society. China, Thailand and Spain are the most important mussel producing countries (Conde 2007). Actually, if only mussels for human consumption are taken into account, the Spanish production is even more relevant. As known, in Spain, mussels (*Mytilus Galloprovincialis*) are mainly cultured in Galicia, where the extensive aquaculture comprises not only farming, but also several processing activities, including mussel purification in dispatch centres, mussel cooking, mussel freezing and mussel canning. From a regional point of view, this network of activities leads to a key economic sector.

Therefore, apart from mussel culture, the Galician mussel sector includes other activities (Franco 2006) which are performed by different economic actors depending on the processing alternative selected for mussel transformation. Thus, three main sub-sectors can be assumed according to the centres where the transformation takes place: (i) dispatch centres sub-sector (fresh mussel market), (ii) canning factories sub-sector, and (iii) mussel cooking plants sub-sector.

In Chapter 3, the mussel farming sub-sector was studied from an LCA perspective, whereas Chapter 4 assesses mussel transformation in dispatch centres, canning factories and mussel cooking plants, as well as mussel consumption in households. In this sense, the LCA of mussels from a sectorial perspective is presented together with the environmental comparison of three different mussel products: fresh mussels, frozen boiled mussels and canned mussels.

The use of LCA is justified because of its proved ability to provide the seafood industry with production chain transparency and accountability (Iles 2007). In fact, LCA results mean a powerful tool for companies and governments in order to facilitate decision and policy making. Hence, the application of this life cycle approach to the mussel sector seeks sustainability in the production and consumption of this seafood (Ayer et al. 2009). Beyond the regional and national relevance of this comprehensive case study, the expected results could be useful for countries with an emerging market for mussels such as China or Chile.

4.2. Methods

The goal of this chapter is to environmentally assess mussel processing and consumption, as well as the mussel sector as a whole.

Mussel processing is directed at the manufacture of the three main mussel products: fresh, canned and frozen mussels. These products present a common origin –mussels cultured in rafts–, but then these farmed mussels are diverted to different mussel sub-sectors. One possibility for cultured mussels is their purification in dispatch centres in order to reach markets as fresh mussels for human consumption. A second alternative would be to send farmed mussels to canning factories where they are processed to obtain the canned product. Finally, the third option involves the processing of mussels in cooking plants. The boiled mussels can be further processed to obtain frozen mussels in the same plant or they can be canned in partial canning factories. The difference between canning factories and partial canning factories lies in that the latter receive mussel meat which has been previously boiled in mussel cooking plants so, unlike canning factories –which directly process farmed mussels–, these partial facilities omit mussel washing, de-clumping, trimming, cooking and dehydrating operations.

In particular, the goal of this chapter comprises the performance of three environmental assessments in order to analyze the impact potentials linked to the following systems:

- Fresh mussel consumption, including a previous stage for mussel purification (culture stage excluded).
- Canned mussel consumption, which previously involves mussel transformation in canning factories (culture stage and mussel shell treatment excluded).
- Frozen mussel consumption, involving mussel transformation in cooking plants prior to consumption (culture stage excluded together with mussel shell treatment).

Additionally, these assessments will lead to an environmental comparison among fresh, canned and frozen mussels, as well as to the LCA of the whole mussel sector. Note that, as reflected in Figure 3.1 (Chapter 3), the whole mussel sector demands the consideration of those systems regarding specific mussel waste treatment (S6 and S7). In this chapter, the implementation of these treatment systems will be directly done when presenting the LCA of the whole sector and the comparative LCA (Iribarren et al. 2010). Nonetheless, Chapter 5 will provide detailed information concerning mussel waste treatment from an LCA perspective.

4.2.1. System boundaries

Fresh mussels from dispatch centres

The study of mussel purification (S2) implies the evaluation of a dispatch centre for molluscs. A dispatch centre is any on-shore or off-shore establishment for the reception, conditioning, washing, cleaning, grading, wrapping and packaging of fresh molluscs for human consumption. This centre is provided with the equipment required to remove pathogens potentially present in molluscs before their consumption as a fresh product.

To make the inventory of system S2, the following operations were considered: mussel haulage, seawater reception, seawater sterilization by chlorine gas dosage, mussel self-purification in pools, seawater discharge (carrying out a control of pathogens in the outlet stream of the pools), and product haulage. Consequently, the following processes were included within the boundaries of S2: production of chlorine gas, electricity and polypropylene (for containers); water discharge; initial and final haulage; and management of organic waste set aside for the production of fish meal and fish oil.

On the other hand, the consumption stage for fresh mussels (S8) took into account: cooking of fresh mussels (equivalent electricity consumption), shopping travel, production of plastic bags and special meshes and labels for fresh mussels, and waste treatment. Processes inside the system boundaries of S8 included: production of polyethylene (HDPE and LDPE), tap water production, electricity production, transport for shopping, wastewater treatment, and management of municipal solid waste.

Canned mussels from canning factories

The study of mussel transformation in canning factories (S3) was performed according to the different stages shown in Figure 4.1 (Xunta de Galicia 2005).

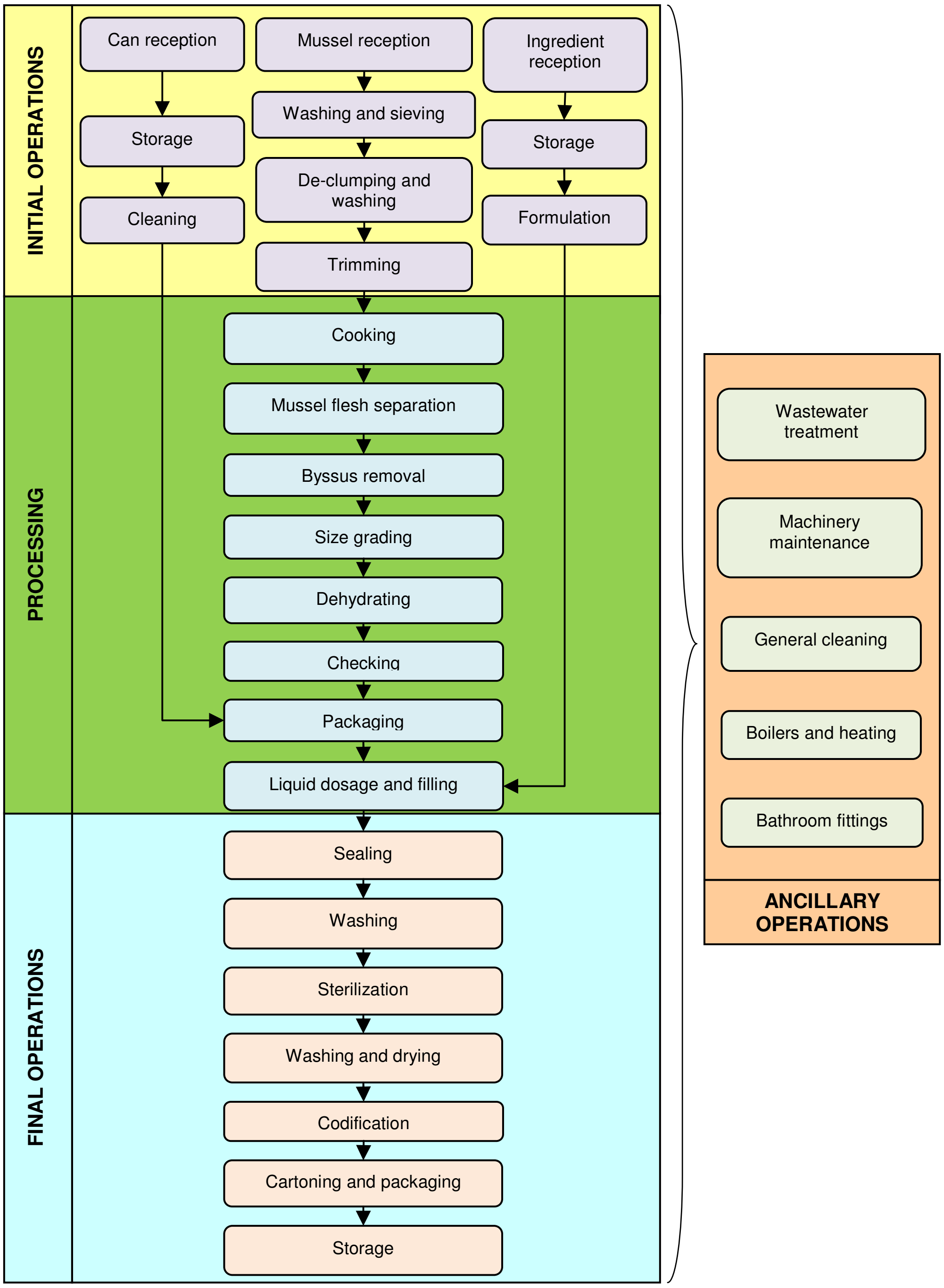

Figure 4.1. *Mussel transformation in canning factories*

For the environmental analysis of system S3, six subsystems were defined (Figure 4.2):

- Subsystem SS3.1 considers mussel haulage from cultivation sites up to the target canning factory. Thus, transport was the only process within the boundaries of this subsystem.
- Subsystem SS3.2 comprises the initial operations carried out in the canning factory: mussel reception, washing and sieving, de-clumping and washing, and trimming. Additionally, other operations such as can reception, storage and cleaning as well as ingredient reception, storage and formulation were considered. Therefore, a wide range of processes were included inside the boundaries of SS3.2: water discharge to the sea, sodium hydroxide production and transport, can production and transport, tap water supply, ingredient production and transport, electricity production, management of mussel organic waste, and waste treatment.
- Subsystem SS3.3 includes the following processing operations: cooking, mussel flesh separation, byssus removal, size grading, dehydrating, checking, packaging, liquid dosage and filling. Processes considered within the boundaries of SS3.3 were: electricity production, management of mussel organic waste, and waste treatment.
- Subsystem SS3.4 comprises the final operations performed in the canning factory: sealing, washing, codification, sterilization, washing and drying, cartoning and packaging, and storage. The corresponding processes within the boundaries of this subsystem were: tap water supply, cardboard production and transport, electricity production, and waste treatment.
- Subsystem SS3.5 includes the ancillary operations: wastewater treatment, bathroom fittings, machinery maintenance, general cleaning, boilers and central heating. A number of processes were included within the boundaries of SS3.5: water discharge and gas emissions; fuel oil production; tap water supply; production and transport of coagulants, flocculants, alkaline cleaner and lubricating oil; electricity production; and waste treatment.
- Subsystem SS3.6 considers canned mussel transport from the canning factory to retailers. Similarly to SS3.1, transport was the only process in the boundaries of this subsystem.

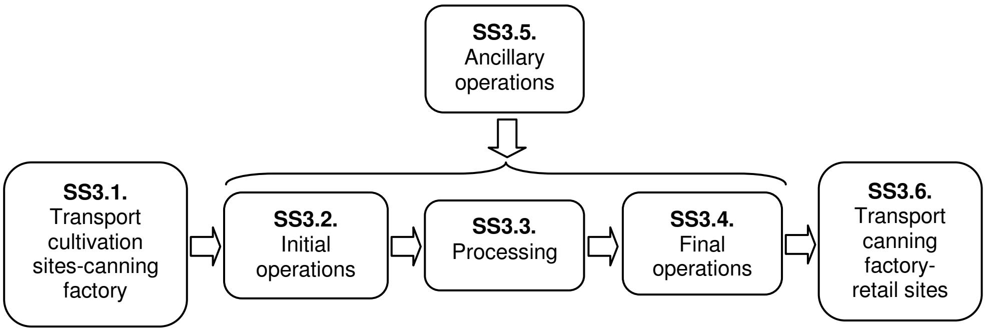

Figure 4.2. *Subsystems for mussel transformation in canning factories (S3)*

Finally, the consumption stage for canned mussels (S9) took into account: shopping travel, production of plastic bags, and waste treatment. Thus, processes within the system boundaries of S9 were: polyethylene production, transport for shopping, and waste treatment for cardboard, tinplate and municipal solid waste.

Mussels from cooking plants

Cooking plants are linked to systems S4, S5, S9 and S10. Regarding the system boundaries of this sub-sector, it should be emphasized that system S4 is divided into two subsystems as shown in Figure 4.3. With respect to system S9, it is a system shared with the previous sub-sector of canning factories, while S10 consists of a single inventory for the consumption of frozen mussels.

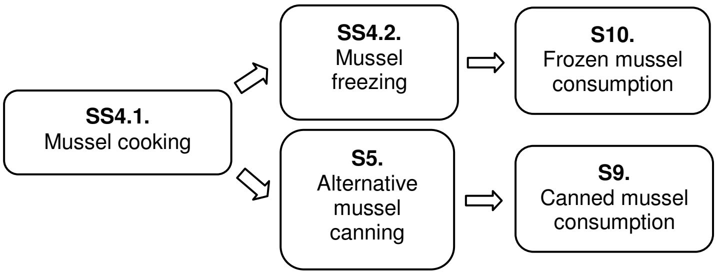

Figure 4.3. *Sub-sector of mussel cooking plants (treatment of mussel wastes excluded)*

As presented in Figure 4.3, system S4 is made up of two subsystems. The first one (SS4.1) covers mussel boiling. Afterwards, the boiled mussel flesh produced in SS4.1 has two main paths. A fraction is destined to frozen mussel production in the cooking plant itself (SS4.2), and the rest is used to produce canned mussels in partial canning factories (S5).

SS4.1 involves the following operations within its boundaries: (i) mussel transport from cultivation sites, (ii) reception, (iii) washing and sieving, (iv) de-clumping and washing, (v) trimming, (vi) cooking, (vii) mussel flesh separation, (viii) byssus removal, (ix) size grading, (x) dehydrating, and (xi) ancillary operations (wastewater treatment, maintenance, etc.).

On the other hand, SS4.2 consists of (i) reception, (ii) cold storage, (iii) processing and packaging, (iv) ancillary operations (cleaning, industrial cold, maintenance, etc.), and (v) transport of frozen boiled mussels to retailers.

Partial canning factories (S5) include: (i) mussel boiled flesh transport from cooking plants, (ii) reception, (iii) packaging (canning), (iv) liquid dosage and filling, (v) sealing, washing and codification, (vi) sterilization, (vii) washing and drying, (viii) cartoning and final packaging, (ix) storage, (x) ancillary operations (wastewater treatment, maintenance, etc.), and (xi) canned mussel transport to retailers.

4.2.2. Functional unit

Fresh mussels from dispatch centres

For the assessment of mussel transformation in dispatch centres (S2) and fresh mussel consumption (S8), the FU was defined as 1 kg of fresh mussels for consumption.

Canned mussels from canning factories

In the case of the environmental evaluation of mussel transformation in canning factories (S3) and canned mussel consumption (S9), the FU was 1 kg of canned mussel flesh (from S3) for consumption.

Frozen mussels from cooking plants

For the study of the environmental performance of mussel transformation in cooking plants to produce frozen mussels (SS4.1 and SS4.2), and frozen mussel consumption (S10), the selected FU was 1 kg of frozen-boiled mussel flesh for consumption.

Whole mussel sector

The accomplishment of a realistic environmental characterization of the whole mussel sector should be based on the commercial behaviour of this sector. Thus, according to specific bibliography (MAPA 2001; Tirado & Macias 2006; Xunta de Galicia 2006, 2007), the distribution of 100 kg of mussels cultured in rafts is as follows: 40 kg are used to produce fresh mussels in dispatch centres, 35 kg are sent to canning factories, 20 kg are processed for frozen mussel production in cooking-freezing plants, while the remaining 5 kg arrive to mussel cooking plants before being transformed in partial canning factories. The LCA of the whole mussel sector is then performed by taking into account 100 kg of mussels from aquaculture and their conventional market share.

Comparison of mussel-based products

The environmental comparison among fresh, canned and frozen mussels is established on the basis of the supply of 8.385 g of proteins. This value corresponds to the amount supplied by one standard round can of mussels (43 g of mussel flesh) (Isabel 2009).

4.2.3. Data acquisition

Fresh mussels from dispatch centres

For mussel purification (S2), data were taken from a dispatch centre where 230 tonnes of purified fresh mussels are annually produced. Moreover, water samples were collected from the input and output streams of the dispatch centre and they were analytically measured. Standard methods (APHA 1995) were used in order to value the main physicochemical parameters: Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD_5), Total Solids, Total Volatile Solids, Total Suspended Solids, Total Volatile Suspended Solids, chloride, Total Organic Carbon (TOC), Total Kjeldahl Nitrogen (TKN), fats and oils, etc. In addition, metal content (Ca, Ni, Cu, Zn, Br, Sr) was determined using X-ray fluorescence.

Canned mussels from canning factories

Data for canned mussel production were gathered in collaboration with a high-profile canning factory which annually produces around 1,180 tonnes of canned mussels (mussel flesh without filling liquid). An exhaustive study of input and output streams was carried out. Furthermore, existing reports were used for the characterization of the corresponding wastewaters (Soto el al. 1990; García-Sandá et al. 2003).

Frozen mussels from cooking plants

Data for mussel cooking (SS4.1) were derived from partial data available for S3 by ruling out the processes after cooking and dehydrating. On the other hand, data for boiled mussel freezing (SS4.2) were based on the information provided by the environmental statements of four factories whose activity concerns seafood freezing (Congalsa 2006, 2007; Frinova 2006; Mascato 2007).

Whole mussel sector

The LCA of the whole mussel sector made use of the data acquired for the previous studies. However, supplementary data were needed for the alternative mussel canning (S5). These data were adapted from data for S3 by means of the exclusion of the processes linked to mussel boiling.

General considerations and assumptions

Electricity production was considered by using the electricity production mix for Spain as presented in the ecoinvent database (Dones et al. 2007).

The quantification of capital goods was avoided (Renou et al. 2008) on the basis of the long life estimated for the installations (more than 20 years in every case), also bearing in mind that the entire production of this type of factories is not exclusively mussel-oriented. For example, this mollusc represents 57.5% of the total production in the dispatch centre, and 6.6% in the canning factory. Capital goods were only considered within the mussel culture system (S1).

In the individual assessments of fresh, canned and frozen mussels, mussel organic waste from processing facilities was considered a by-product for the production of fish meal and fish oil. Hence, in these assessments, this by-product was regarded as a product avoiding the production of the organic input associated with fish meal production (Nielsen et al. 2003). This means that allocation was avoided by a system expansion assuming that mussel organic waste equals the input of organic matter which is processed in fish meal plants; that is, in the case of fish meal production as reported by Nielsen et al. (2003): 1 kg of mussel organic waste replaces 1 kg of sand eel (but not 1 kg of fish meal). This rough assumption is avoided in the LCA of the whole mussel sector and in the comparative LCA by following the guidelines provided by Iribarren et al. (2010) for the implementation of mussel waste treatment.

Finally, for mussel consumption systems (S8, S9 and S10), different sources were analyzed including studies on seafood (Hospido et al. 2006), statistical data (Xunta de Galicia 2006) and reports on development and trends in mollusc markets (Tirado & Macias 2006; Illescas et al. 2007).

4.2.4. Life cycle inventory

Fresh mussels from dispatch centres

As indicated, inventory data for mussel purification were gathered from a Galician dispatch centre with an annual production of 230 tonnes of fresh purified mussels. Data dealt with several issues such as: production of purified mussels; consumption of water, electricity and chlorine; distance from mussel cultivation sites; and distance to the final distribution points (retailers). Moreover, water samples collected from the input and output streams of the dispatch centre were analytically measured. Thus, inventory data for mussel purification are presented in Table 4.1, while inventory data for the consumption of fresh purified mussels are gathered in Table 4.2.

Table 4.1. *Inventory data for mussel purification (S2)*

INPUTS					
From the technosphere			**From the environment**		
Materials			**Raw materials**		
1. Chemicals and other materials			1. Seawater	7.80	m^3
Chlorine gas	20.00	g	Total COD	7.86	mg O_2
Containers (PP)	12.50	g	BOD_5	0.00	mg O_2
2. Mussels of commercial size	1.22	kg	Dissolved solids	1.38	g
Energy			Suspended solids	0.04	g
1. Electric energy	5.11	kWh	Chloride	0.67	g
Transport			TOC	0.21	mg C
1. Mussel reception	9.74	m	Organic nitrogen	0.08	mg N
2. Purified mussel dispatch	283.33	m	Fats	16.36	mg
			Calcium	13.57	mg
			Nickel	0.33	mg
			Copper	0.44	mg
			Zinc	0.07	mg
			Bromine	2.42	mg
			Strontium	0.19	mg
			2. Land use	0.03	m^2

Table 4.1. *Inventory data for mussel purification (S2) (cont.)*

OUTPUTS					
To the technosphere			**To the environment: emissions to the ocean**		
Final product			1. Wastewater (7.80 m^3)		
1. Dispatched and purified mussel	1.00	kg	Total COD	5.79	mg O_2
By-product			BOD_5	0.00	mg O_2
1. Mussel discarded for fish meal	8.70	g	Dissolved solids	1.42	g
			Suspended solids	0.07	g
			Chloride	0.67	g
			TOC	0.19	mg C
			Organic nitrogen	0.04	mg N
			Fats	2.05	mg
			Calcium	10.17	mg
			Nickel	0.32	mg
			Copper	0.05	mg
			Zinc	0.05	mg
			Bromine	1.93	mg
			Strontium	0.18	mg

Table 4.2. *Inventory data for fresh mussel consumption (S8)*

INPUTS FROM THE TECHNOSPHERE		
Materials		
1. Dispatched and purified mussel	1.00	kg
2. Mesh and label (HDPE)	3.84	g
3. Fresh water	1.72	kg
4. Plastic bags (LDPE)	3.80	g
Transport		
1. Shopping travel	0.05	m
Energy		
1. Electric energy	0.07	kWh
OUTPUTS TO THE TECHNOSPHERE		
Waste to treatment		
1. Municipal solid waste: mesh and label	3.84	g
2. Municipal solid waste: mussel shell	0.30	kg
3. Municipal solid waste: plastic bags	3.80	g
4. Fresh water	1.72	kg

Canned mussels from canning factories

It was necessary to analyze the input/output flows of a canning factory with the purpose of inventorying the production of canned mussels in S3. This exhaustive study allowed the making of partial inventories for the six subsystems defined for mussel transformation in canning factories (Table 4.3a-f). Finally, inventory data for the consumption of canned mussels from S3 are presented in Table 4.4.

Table 4.3a. *Inventory data for mussel transformation in canning factories: SS3.1*

INPUTS			OUTPUTS		
From the technosphere			To the technosphere		
Transport			**Product**		
1. Mussel up to the factory	0.43	km	1. Transported mussel of commercial size	12.67	kg
Material					
1. Mussel of commercial size	12.67	kg			

Table 4.3b. *Inventory data for mussel transformation in canning factories: SS3.2*

INPUTS					
From the technosphere			From the environment		
Materials			**Matter**		
1. Chemicals and other materials			1. Water		
Soda	1.17	g	Seawater	6.79	dm^3
Empty cans (tinplate)	0.66	kg	**Surface**		
2. Raw materials			1. Land use	0.08	dm^2
Transported mussel of commercial size	12.67	kg			
Oils	0.25	kg			
3. Water					
Fresh water	0.61	dm^3			
Energy					
1. Electric energy	0.30	kWh			
Transport					
1. Ingredients	$2.52 \cdot 10^{-4}$	t·km			
2. Containers	0.78	t·km			
3. Soda	$3.42 \cdot 10^{-4}$	t·km			

Table 4.3b. *Inventory data for mussel transformation in canning factories: SS3.2 (cont.)*

OUTPUTS					
To the technosphere			**To the environment**		
Products			**Emissions to the ocean** (6.79 dm^3)		
1. Mussel for cooking	10.44	kg	1. Suspended solids	6.08	g
2. Sauce (water and oils)	0.86	kg	2. Total COD	4.50	g O_2
3. Clean cans	0.66	kg	3. Chloride	0.13	g
By-products					
1. Mussel debris from washing	1.90	kg			
2. Mussel organic waste	0.34	kg			
Waste to treatment (authorized agent)					
1. Stainless metallic waste	0.11	g			
2. Iron metallic waste	0.75	g			
3. Defective cans (tinplate)	3.08	g			
4. Water from racking systems cleaning	1.96	g			
5. Plastics	7.83	g			
6. Lead batteries	$8.91\cdot10^{-8}$	units			
7. Dry batteries	$8.91\cdot10^{-6}$	units			
8. Electronic equipment	$4.45\cdot10^{-8}$	units			
9. Fluorescent tubes	$3.56\cdot10^{-6}$	units			

Table 4.3c. *Inventory data for mussel transformation in canning factories: SS3.3*

INPUTS					
From the technosphere			**From the environment**		
Materials			**Matter**		
1. Raw materials			1. Water		
Mussel for cooking	10.44	kg	Seawater	0.21	dm^3
Clean cans	0.66	kg	**Surface**		
Sauce	0.86	kg	1. Land use	0.08	dm^2
Energy					
1. Electric energy	0.49	kWh			
2. Thermal energy (from SS3.5)	1.19	MJ			

Table 4.3c. *Inventory data for mussel transformation in canning factories: SS3.3 (cont.)*

OUTPUTS					
To the technosphere			**Effluent to wastewater treatment plant**		
Product			**Water to treatment** (0.21 dm^3)		
1. Mussel in unsealed can (sauce and can excluded)	1.00	kg	1. Suspended solids	0.27	g
By-products			2. Total COD	3.76	g O_2
1. Mussel organic waste	0.34	kg	3. Chloride	2.94	kg
2. Mussel shell	2.38	kg			
Waste to treatment (authorized agent)					
1. Stainless metallic waste	0.11	g			
2. Iron metallic waste	0.75	g			
3. Lead batteries	$8.92\cdot10^{-8}$	units			
4. Dry batteries	$8.92\cdot10^{-6}$	units			
5. Electronic equipment	$4.46\cdot10^{-8}$	units			
6. Fluorescent tubes	$3.57\cdot10^{-6}$	units			

Table 4.3d. *Inventory data for mussel transformation in canning factories: SS3.4*

INPUTS					
From the technosphere			**From the environment**		
Materials			**Surface**		
1. Raw materials			1. Land use	0.07	dm^2
Mussel in unsealed can	1.00	kg			
2. Water					
Fresh water	0.31	dm^3			
3. Others					
Cartons	0.10	kg			
Energy					
1. Electric energy	0.53	kWh			
2. Thermal energy (from SS3.5)	1.79	MJ			
Transport					
1. Cartons	0.01	t·km			

Table 4.3d. *Inventory data for mussel transformation in canning factories: SS3.4 (cont.)*

OUTPUTS					
To the technosphere			**Effluent to wastewater treatment plant**		
Product			**Water to treatment**	0.31	dm^3
1. Canned mussel flesh	1.00	kg			
Waste to treatment (authorized agent)					
1. Stainless metallic waste	0.09	g			
2. Iron metallic waste	0.65	g			
3. Paper and cardboard	22.38	g			
4. Lead batteries	$7.72\cdot10^{-8}$	units			
5. Dry batteries	$7.72\cdot10^{-6}$	units			
6. Electronic equipment	$3.86\cdot10^{-8}$	units			
7. Fluorescent tubes	$3.09\cdot10^{-6}$	units			
8. Ink cartridges	$7.27\cdot10^{-6}$	units			

Table 4.3e. *Inventory data for mussel transformation in canning factories: SS3.5*

INPUTS					
From the technosphere			**From the environment**		
Materials and fuels			**Surface**		
1. Chemicals and other materials			1. Land use	0.02	dm^2
Alkaline cleaner	1.23	g			
Aluminium polychloride	0.22	cm^3			
Anionic gel	3.36	mm^3			
Lubricant oil	0.03	g			
2. Wastewater					
Effluent from SS3.3	0.21	dm^3			
Effluent from SS3.4	0.31	dm^3			
3. Fresh water	13.47	dm^3			
4. Fuel oil	0.07	kg			
Energy					
1. Electric energy	0.03	kWh			
Transport					
1. Flocculants	$1.65\cdot10^{-6}$	t·km			
2. Coagulants	$1.41\cdot10^{-4}$	t·km			
3. Lubricant oil	$8.56\cdot10^{-7}$	t·km			
4. Alkaline cleaner	$7.53\cdot10^{-5}$	t·km			

Table 4.3e. *Inventory data for mussel transformation in canning factories: SS3.5 (cont.)*

OUTPUTS					
To the technosphere			**To the environment**		
Product			**Emissions to the ocean** (13.50 dm^3)		
1. Thermal energy	2.98	MJ	1. Fats	0.02	g
Waste to treatment (authorized agent)			2. BOD_5	0.18	g O_2
1. Stainless metallic waste	0.03	g	3. Total COD	1.28	g O_2
2. Iron metallic waste	0.20	g	4. Suspended solids	0.65	g
3. Water from bathroom fittings	3.28	cm^3	5. Total phosphorus	2.61	mg
4. Sludge and fats from wastewater treatment	17.77	g	6. Ammoniacal nitrogen	0.12	g
5. Lubricant oils	0.08	g	**Emissions to the atmosphere**		
6. Lead batteries	$2.43 \cdot 10^{-8}$	units	1. CO_2	409.23	g
7. Dry batteries	$2.43 \cdot 10^{-6}$	units	2. SO_2	0.47	g
8. Electronic equipment	$1.21 \cdot 10^{-8}$	units	3. COV	1.12	mg
9. Fluorescent tubes	$9.72 \cdot 10^{-7}$	units	4. NO_x	0.13	g
			5. CO	0.03	g

Table 4.3f. *Inventory data for mussel transformation in canning factories: SS3.6*

INPUTS			OUTPUTS		
From the technosphere			**To the technosphere**		
Transport			**Product**		
1. Canned mussels up to retail sites	0.10	km	1. Dispatched and canned mussel flesh	1.00	kg
Material					
1. Canned mussel flesh	1.00	kg			

Table 4.4. *Inventory data for the consumption of canned mussels from S3*

INPUTS FROM THE TECHNOSPHERE		
Materials		
1. Dispatched and canned mussel flesh	1.00	kg
2. Plastic bags (LDPE)	3.80	g
Transport		
1. Shopping travel	0.05	m

Table 4.4. *Inventory data for the consumption of canned mussels from S3 (cont.)*

OUTPUTS TO THE TECHNOSPHERE		
Waste to treatment		
1. Cans (tinplate) to recycling	333.87	g
2. Cans (tinplate) to landfill	191.08	g
3. Carton to recycling	51.22	g
4. Carton to landfill	31.13	g
5. Municipal solid waste: plastic bags	3.80	g

Frozen mussels from cooking plants

Table 4.5a-b gathers the inventories for the subsystems involved in frozen mussel production. On the other hand, Table 4.6 shows the inventory for the consumption of frozen mussels in households.

Table 4.5a. *Inventory data for frozen mussel production: SS4.1*

INPUTS					
From the technosphere			**From the environment**		
Materials and fuels			**Matter**		
1. Chemicals and other materials			1. Water		
Alkaline cleaner	0.61	g	Seawater	3.89	dm^3
Aluminium polychloride	0.14	cm^3	**Surface**		
Anionic gel	2.14	mm^3	1. Land occupation	0.12	dm^2
Soda	1.17	g			
Lubricant oil	0.01	g			
2. Raw materials					
Mussels of commercial size	12.67	kg			
3. Fresh water	5.69	dm^3			
4. Fuel oil	0.03	kg			
Energy					
1. Electric energy	0.43	kWh			
2. Thermal energy	1.19	MJ			
Transport					
1. Mussels up to the factory	0.80	t·km			
2. Soda	$3.42\cdot10^{-4}$	t·km			
3. Flocculant	$1.05\cdot10^{-6}$	t·km			
4. Coagulant	$8.97\cdot10^{-5}$	t·km			
5. Lubricant oil	$3.42\cdot10^{-7}$	t·km			
6. Alkaline cleaner	$3.73\cdot10^{-5}$	t·km			

Table 4.5a. *Inventory data for frozen mussel production: SS4.1 (cont.)*

OUTPUTS					
To the technosphere			**To the environment**		
Product			**Emissions to the atmosphere**		
1. Boiled mussel flesh	1.00	kg	1. CO_2	164.43	g
By-products			2. SO_2	0.19	g
1. Mussel shell	2.38	kg	3. VOC	0.45	mg
2. Mussel debris	1.90	kg	4. NO_x	0.05	g
3. Mussel organic waste	0.34	kg	5. CO	0.01	g
Intermediate product			**Emissions to the ocean**		
1. Thermal energy	1.19	MJ	1. Fats	0.01	g
Waste to treatment (authorized agent)			2. BOD_5	0.12	g O_2
1. Stainless metallic waste	0.17	g	3. COD	3.68	g O_2
2. Iron metallic waste	1.16	g	4. Suspended solids	4.29	g
3. Water from racking systems cleaning	1.96	g	5. Total phosphorus	1.66	mg
4. Water from bathroom fittings	1.62	cm^3	6. Ammoniacal nitrogen	0.08	g
5. Lead batteries	$1.39\cdot10^{-7}$	units	7. Chloride	0.08	kg
6. Sludge and fats from wastewater treatment	11.32	g			
7. Lubricant oils	0.03	g			
8. Fluorescent tubes	$5.55\cdot10^{-6}$	units			
9. Dry batteries	$1.39\cdot10^{-5}$	units			
10. Electronic equipments	$6.39\cdot10^{-8}$	units			

Table 4.5b. *Inventory data for frozen mussel production: SS4.2*

INPUTS					
Materials and fuels from the technosphere			**Energy from the technosphere**		
1. Raw material			1. Electric energy	0.40	kWh
Boiled mussel flesh	1.00	kg	2. Thermal energy	0.42	MJ
2. Fresh water	2.75	dm^3	**Transport**		
3. Containers			1. Frozen mussel flesh up to the retail site	0.65	t·km
Paperboard	50.27	g	2. Plastics	$0.13\cdot10^{-2}$	t·km
PET	0.20	g	3. Paperboard	$0.60\cdot10^{-2}$	t·km
LDPE	0.32	g	**From the environment: surface**		
HDPE	1.73	g	1. Land occupation	0.08	dm^2
Other plastics	8.44	g			

Table 4.5b. *Inventory data for frozen mussel production: SS4.2 (cont.)*

OUTPUTS					
To the technosphere			**To the environment**		
Final product			**Emissions to the ocean (2.38 dm^3)**		
1. Dispatched frozen-boiled mussel flesh	1.00	kg	1. Suspended solids	0.29	g
Waste to treatment			2. COD	1.46	g O_2
1. Plastic waste	1.33	g	3. BOD_5	0.86	g O_2
2. Paperboard waste	1.33	g	4. Fats	0.05	g
3. Wood waste	0.43	g	5. Detergents	$0.10\cdot10^{-2}$	g
4. Sludge from wastewater treatment	27.94	g	6. Ammonium	$0.56\cdot10^{-2}$	g
5. Scrap	0.24	g	7. Total phosphorus	$0.43\cdot10^{-2}$	g
6. Hazardous waste: mineral oil	0.07	g			
7. Hazardous waste: material contaminated with hydrocarbon compounds	$0.03\cdot10^{-2}$	g			
8. Hazardous waste: batteries	$0.01\cdot10^{-2}$	g			
9. Hazardous waste: fluorescent tubes	$0.12\cdot10^{-2}$	g			
10. Hazardous waste: used solvent	$0.89\cdot10^{-2}$	g			
11. Hazardous waste: containers and absorbents	$4.62\cdot10^{-2}$	g			

Table 4.6. *Inventory data for frozen mussel consumption*

INPUTS FROM THE TECHNOSPHERE		
Materials		
1. Dispatched frozen-boiled mussel flesh from SS4.2	1.00	kg
2. Plastic bags (LDPE)	3.80	g
Transport		
1. Shopping travel	0.14	m
OUTPUTS TO THE TECHNOSPHERE		
Waste to treatment		
1. Plastic to recycling	2.41	g
2. Plastic to landfill	9.07	g
3. Carton to recycling	36.90	g
4. Carton to landfill	17.13	g
5. Municipal solid waste: plastic bags	3.80	g

Additional information for the whole mussel sector

To perform the LCA of the whole mussel sector, the inventory for canned mussel production in partial canning factories was needed. Table 4.7 presents this inventory.

Table 4.7. *Inventory data for canned mussel production in partial canning factories (S5)*

INPUTS					
From the technosphere			**From the environment**		
Materials and fuels			**Matter**		
1. Chemicals and other materials			1. Water		
Alkaline cleaner	0.62	g	Seawater	3.11	dm^3
Aluminium polychloride	0.08	cm^3	**Surface**		
Anionic gel	1.22	mm^3	1. Land occupation	0.12	dm^2
Empty cans (tinplate)	0.66	kg			
Lubricant oil	0.02	g			
2. Raw materials					
Boiled mussel flesh	1.34	kg			
Oils	0.25	kg			
3. Water					
Fresh water	8.70	dm^3			
4. Cardboard	0.10	kg			
5. Fuel					
Fuel oil	0.04	kg			
Energy					
1. Electric energy	0.93	kWh			
2. Thermal energy	1.79	MJ			
Transport					
1. Boiled mussel flesh up to the factory	0.10	t·km			
2. Canned mussels up to the retail site	0.10	km			
3. Ingredients	$2.52\cdot10^{-4}$	t·km			
4. Containers	0.78	t·km			
5. Cardboard	0.01	t·km			
6. Flocculant	$5.99\cdot10^{-7}$	t·km			
7. Coagulant	$5.12\cdot10^{-5}$	t·km			
8. Lubricant oil	$5.14\cdot10^{-7}$	t·km			
9. Alkaline cleaner	$3.80\cdot10^{-5}$	t·km			

Table 4.7. *Inventory data for canned mussel production in partial canning factories (S5) (cont.)*

OUTPUTS					
To the technosphere			**To the environment**		
Final product			**Emissions to the atmosphere**		
1. Dispatched and canned mussel flesh	1.00	kg	1. CO_2	245.80	g
By-product			2. SO_2	0.28	g
1. Mussel organic waste	0.34	kg	3. VOC	0.67	mg
Intermediate product			4. NO_x	0.08	g
1. Thermal energy	1.79	MJ	5. CO	0.02	g
Waste to treatment (authorized agent)			**Emissions to the ocean**		
1. Stainless metallic waste	0.17	g	1. Fats	$0.85 \cdot 10^{-2}$	g
2. Iron metallic waste	1.19	g	2. BOD_5	0.07	g O_2
3. Defective cans (tinplate)	3.08	g	3. COD	2.10	g O_2
4. Water from bathroom fittings	1.65	cm^3	4. Suspended solids	2.45	g
5. Paper and cardboard	22.38	g	5. Total phosphorus	0.95	mg
6. Plastics	7.83	g	6. Ammoniacal nitrogen	0.04	g
7. Lead batteries	$1.41 \cdot 10^{-7}$	units	7. Chloride	0.05	kg
8. Sludge and fats from wastewater treatment	6.46	g			
9. Lubricant oils	0.05	g			
10. Fluorescent tubes	$5.65 \cdot 10^{-6}$	units			
11. Dry batteries	$1.41 \cdot 10^{-5}$	units			
12. Electronic equipment	$7.06 \cdot 10^{-8}$	units			
13. Ink cartridges	$7.27 \cdot 10^{-6}$	units			

Finally, it should be noted that the study of the whole mussel sector considers that 12.50% of the consumed canned mussels comes from partial factories (Tirado & Macias 2006; Xunta de Galicia 2007). In this sense, when characterizing the whole sector, the inventory for system S9 is just as that in Table 4.4 but, instead of assuming 1.00 kg of canned mussels from S3, the following origin should be specified: 0.875 kg from S3 and 0.125 kg from S5.

4.3. Results

As in the previous chapter, SimaPro 7 was the software used for the computational implementation of the different inventories (Goedkoop et al. 2008). The ecoinvent database was also chosen for background processes, just resorting to other databases when necessary, specifically for oil as an ingredient in the production of canned mussels (data adapted from LCA Food data base) and cans for the canning factory (BUWAL 250).

Classification and characterization following ISO guidelines were applied to analyze the potential environmental impact of inputs and outputs from the LCIs. This set of LCAs was performed using the CML method. AP, ODP, ADP, GWP, EP, POFP, FETP, METP, TETP and HTP were the impact categories assessed.

4.3.1. Fresh mussels from dispatch centres

The characterization results for mussel purification (S2) and fresh mussel consumption (S8) were studied together.

Figure 4.4 clearly illustrates the contribution of fresh mussel purification and consumption to the selected impact categories. A much greater relevance of system S2 for each of the impact categories is observed, which included a positive potential impact for ADP due to the consideration of mussel organic waste as a by-product for the production of fish meal and fish oil. Note that mussel culture stage (S1) was omitted from this analysis.

Furthermore, LCA characterization results led to the identification of the main processes contributing to undesirable environmental impacts linked to fresh mussels. These processes are summarized in Figure 4.5. ADP is not represented in this figure since a desirable potential impact was found because of the consideration of mussel organic waste as a by-product avoiding the input associated with fish meal production (Nielsen et al. 2003); this fact captured the total contribution to ADP.

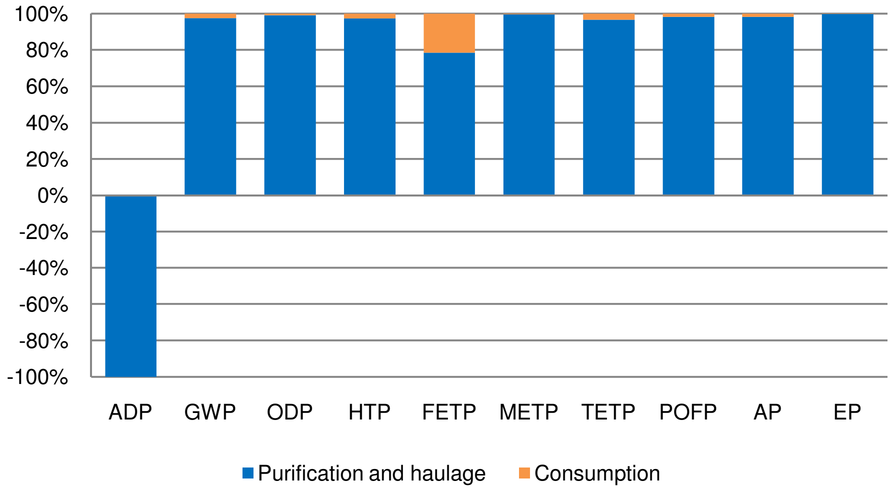

Figure 4.4. *Contributions to the environmental impact potentials: S2 and S8*

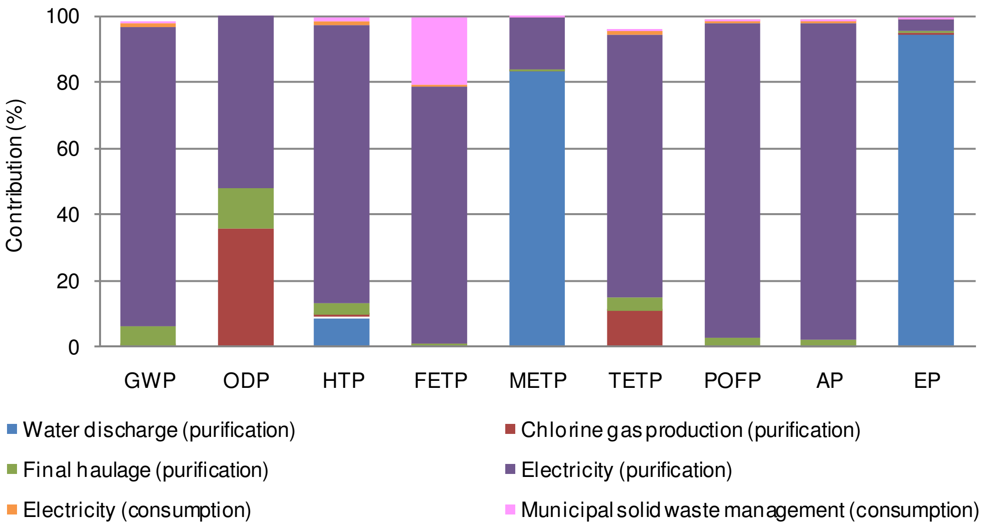

Figure 4.5. *Process contribution for fresh mussels*

As observed in Figure 4.5, electricity use in mussel purification stood out as the main source of potential impact. This process prevailed for GWP (contribution of more than 90% to the potential impact for this category), ODP (52%), POFP (95%), AP (95%), HTP (84%), FETP (77%) and TETP (79%).

Moreover, electricity production for mussel purification accounted for 16% of the potential impact for METP and for 4% of the potential impact for EP.

On the other hand, water discharge to the sea in the dispatch centre was found to be the main contributor to two impact categories: EP (95% of the total impact for this category) and METP (84%).

To a lesser extent, other processes contributed to the potential environmental impacts. For example, chlorine gas production accounted for a contribution of 36% to ODP, 11% to TETP, and 1% to HTP. Other examples are final haulage from the dispatch centre (contribution of 6% to GWP, 12% to ODP, 3% to POFP, 2% to AP, 3% to HTP and 4% to TETP), management of municipal solid waste from household consumption (contribution of 20% to FETP and 1% to HTP), electricity use for fresh mussel consumption (contribution of 1% to GWP, POFP, AP, HTP, FETP and TETP) or polypropylene production for containers (contribution of 2% TETP).

4.3.2. Canned mussels from canning factories

The characterization results for mussel transformation in canning factories (S3) and canned mussel consumption (S9) were also analyzed. Figure 4.6 illustrates the contribution of S3 and S9 to the impact categories. The contribution related to system S3 was analyzed distinguishing initial haulage, initial operations, processing, final operations, ancillary operations and final haulage. A much greater relevance of system S3 for every impact category was concluded as compared to household consumption of canned mussels, whose major potential contributions were around 10% for both FETP and TETP. The culture stage (S1) was omitted from this analysis, as well as the treatment of mussel shells from canning factories.

According to Figure 4.6, initial operations subsystem (SS3.2) prevailed for ADP, GWP, POFP, AP and EP, while ancillary operations subsystem (SS3.5) did for ODP and TETP. With regard to HTP, FETP and METP, impact contribution was found to be mainly shared by initial operations (SS3.2), processing (SS3.3) and final operations (SS3.4). The processing subsystem (SS3.3) showed a desirable potential impact on ADP and ODP due to the consideration of mussel organic waste as a by-product avoiding the input associated with fish meal production. Finally, haulage contributions to the potential environmental impacts were not as noticeable as those related to other subsystems; initial haulage (SS3.1) was found to contribute more than final haulage (SS3.6).

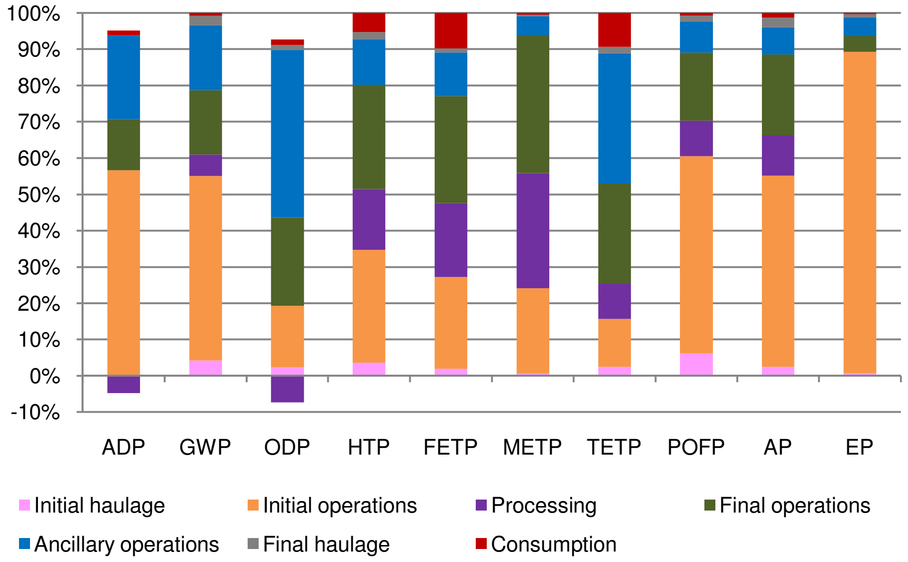

Figure 4.6. *Contributions to the environmental impact potentials: S3 (subsystems) and S9*

The summary of the main processes which contributed to the potential environmental impacts linked to canned mussels from canning factories is presented in Table 4.8. From this summary, it is observed that the origin of ADP was mainly related to three processes: can production (SS3.2), oil production (SS3.2) and fuel oil production (SS3.5).

Oil production was also found as the major contributor to GWP; other processes with a significant contribution to this impact category were the production and transport of cans (SS3.2), gas release in SS3.5, and electricity production for SS3.2, SS3.3 and SS3.4.

Fuel oil production was identified as the main process contributing to ODP. Oil production also showed a relevant contribution to this impact category.

For the four toxicity and eco-toxicity impact categories, it was shown that the three electricity production processes linked to final operations, processing and initial operations were the key contributors. Another process with a relevant contribution to these impact categories was can transport. Regarding TETP, it should be stressed that sludge management (SS3.5) was the major potential contributor.

For POFP, AP and EP, one process emerged as the main contributor: oil production. Moreover, electricity production processes (SS3.2, SS3.3 and SS3.4) were the main additional contributors to these environmental impact categories.

Table 4.8. *Main processes contributing to the potential environmental impacts for S3 and S9, and their contribution (%)*

SS and Process	Category	ADP (%)	GWP (%)	ODP (%)	HTP (%)	FETP (%)	METP (%)	TETP (%)	POFP (%)	AP (%)	EP (%)
Initial haulage (SS3.1)	Transport	0.00	4.54	3.45	3.74	1.97	0.63	2.87	6.39	2.55	0.70
Initial operations (SS3.2)	Can production	37.85	9.15	0.64	9.14	0.52	1.43	5.65	1.90	1.88	0.27
	Oil production	37.90	32.94	28.95	0.01	0.40	-0.39	-10.69	42.69	38.02	86.98
	Can transport	0.00	9.59	7.71	13.59	12.87	3.16	13.37	6.02	8.61	2.59
	Electricity production	0.00	5.19	1.59	12.31	13.85	20.06	8.02	6.93	8.90	0.63
Processing (SS3.3)	Electricity production	0.00	8.52	2.60	20.22	22.73	32.93	13.16	11.37	14.61	1.04
Final operations (SS3.4)	Cardboard production	5.93	1.95	5.98	2.76	1.14	1.08	1.19	3.61	3.90	1.13
	Electricity production	0.00	9.20	2.81	21.84	24.56	35.57	14.22	12.29	15.79	1.12
Ancillary operations (SS3.5)	Emissions to the environment	0.00	15.68	0.00	0.07	0.00	0.00	0.00	3.18	3.90	0.39
	Fuel oil production	28.24	1.61	68.03	10.63	6.61	2.17	8.67	3.22	1.99	0.22
	Tap water production	0.00	0.14	0.04	0.45	1.00	0.35	0.65	0.17	0.12	0.01
	Electricity production	0.00	0.57	0.17	1.35	1.51	2.19	0.88	0.76	0.97	0.07
	Sludge management	0.22	1.13	0.35	0.36	2.89	0.45	31.16	1.42	0.74	4.54
Final haulage (SS3.6)	Transport	0.00	2.86	2.21	2.05	1.24	0.37	2.03	1.78	2.71	0.85
Consumption (S9)	Municipal solid waste management	0.00	0.07	0.00	0.35	9.53	0.31	0.05	0.01	0.01	0.02
	Tinplate waste treatment	1.39	0.45	1.70	4.91	0.49	0.17	10.84	0.44	0.99	0.30

It is observed that, even though Table 4.8 means a selection of processes, it is possible to identify a shorter set of key processes. This set should include four processes from initial operations (oil production, electricity production, can production and can transport), one process from processing (electricity production), one process from final operations (electricity production), and, finally, one process from ancillary operations (fuel oil production).

4.3.3. Frozen mussels from cooking plants

The characterization results for frozen mussel production (SS4.1 and SS4.2) and consumption (S10) were also analyzed. For this assessment, the mussel culture stage (S1) was omitted together with the treatment of mussel shells from the cooking subsystem.

Figure 4.7 shows the contribution of cooking (SS4.1) and freezing (SS4.2) subsystems to the impact potentials, as well as the contribution related to household consumption of frozen mussels (S10). The environmental relevance of consumption was clearly lower than that of mussel processing. In fact, all the potential contributions of S10 were below 5%, except that for FETP (12%).

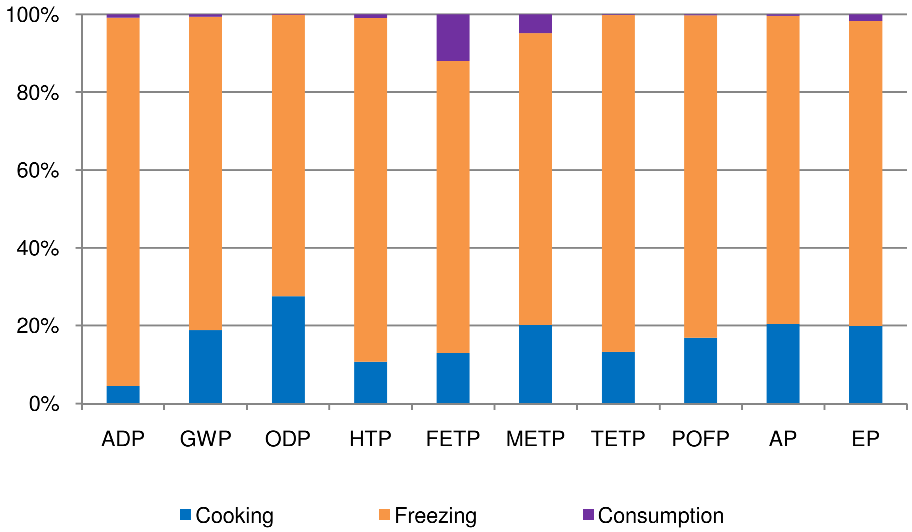

Figure 4.7. *Contributions to the environmental impact potentials: SS4.1, SS4.2 and S10*

According to Figure 4.7, freezing subsystem prevailed for all impact categories, with contribution percentages ranging from 72% for ODP to 95% for ADP. The contribution range for cooking covered from 4% for ADP to 28% for ODP.

Energy demand for freezing arose as the main responsible for the potential impacts related to frozen mussel production.

4.4. Discussion and identification of improvement potentials

4.4.1. Mussel processing and consumption

Once the characterization values were obtained, the identification of hot spots for the three mussel-based products was possible. Nevertheless, in order to complete the environmental contribution analysis and identify the most advisable improvement actions, the implementation of the mussel culture stage as well as of the treatment of mussel shell and mussel organic waste should be taken into account. In this sense, mussel cultivation as established in Chapter 3 was included. On the other hand, mussel waste treatment was integrated according to Iribarren et al. (2010); further details concerning this issue are supplied in Chapter 5. As a result, new characterization results for fresh and canned mussels were obtained.

Figure 4.8 illustrates the potential contribution of culture, processing and consumption to the different impact categories for fresh, canned and frozen mussels.

As observed, a common feature for the three mussel products was the low potential contribution linked to household consumption, except for FETP in the case of fresh mussels, where consumption accounted for more than 20% of the potential impact for this category, which is mainly due to municipal solid waste treatment.

For canned and frozen mussels, Figure 4.8 shows that processing entailed potentially favourable environmental impacts (i.e., desirable effects) regarding AP and EP. This observation is due to the assumption of avoided burdens when mussel pâté production is chosen as the treatment option for mussel organic waste, as discussed in Chapter 5.

Figure 4.8. *Contribution of culture, processing and consumption to the potential environmental impact of mussel products*

The results for canned and frozen mussels report a similar environmental performance (Figure 4.8), where culture was the main contributor to the potential environmental impact, except for TETP, which was mainly influenced by processing. Therefore, the improvement potentials for canned/frozen mussel activities should consider not only actions on canning factories and cooking-freezing facilities (Thrane 2006), but primarily measures focused on mussel farming. Thus, the main improvement actions should be centred on the optimization of diesel consumption levels for boats, and on the minimization of the energy and iron demand for capital goods. Additional improvement potentials would be the optimization of the oil and can demand for canning factories, and the minimization of the electricity and fuel oil demand for operations in canning factories and cooking-freezing plants. It is important to remark that the environmental role of can production is highly conditioned by the chosen database (BUWAL250), and improvements in the can inventory would involve greater contribution percentages of this process to the potential environmental impact for canned mussels, as shown in Chapter 10 for the global warming category. In this sense, improvement actions on packaging material should not be ruled out.

On the contrary, in the case of fresh mussels, Figure 4.8 shows that processing prevailed for all impact categories. Excluding METP and EP, this fact is due to the unsustainable consumption of electricity within the dispatch centres; on the other hand, for METP and EP, this observation is linked to the discharge of water from dispatch centres. Consequently, the main improvement potentials for fresh mussels should be focused on mussel purification. In this sense, the main action should consist of the minimization of electricity use in dispatch centres by upgrading their electric systems and providing them with frequency inverters. Additional improvements in mussel purification might be achieved by optimizing the consumption levels of chlorine gas in dispatch centres (environmental assessments regarding other type of agents to remove pathogens in seawater should also be undertaken), reducing water consumption for dispatch centres (an assessment concerning the possibility of treating the output stream could also be considered) and revising the logistical planning for the final haulage from dispatch centres to retailers (Sim et al. 2007). In addition, further improvement actions on mussel culture would help to mitigate the environmental impacts, in particular for ADP and ODP. Thus, the minimization of the amount of diesel used for vessel operation in mussel farming should also be encouraged.

When the mussel culture stage and mussel waste treatment were introduced into the LCA model, mussel purification remained the key contributor to potential environmental impacts while mussel canning was shown to be less contributing when compared to mussel cultivation. This fact might be considered unexpected; however, it clearly captures the current arrangement of the Spanish mussel sector where the mussel canning sub-sector is made up of high-profile companies with large production and a relatively optimized performance (Barros et al. 2009). On the contrary, the fresh mussel sub-sector involves dispatch centres; these facilities usually involve some kind of traditional family business. Thus, dispatch centres normally work far from optimized conditions. This results in high consumption levels. In particular, the life cycle study on fresh mussels revealed an environmentally unsustainable electricity consumption associated with the operation within dispatch centres, where electric systems are usually obsolete and lacking in frequency inverters.

4.4.2. Whole mussel sector

According to the FU defined for the LCA of the whole mussel sector, Figure 4.9 illustrates the corresponding environmental characterization given the conventional distribution for the Spanish mussel market. The contribution of each of the sub-sectors to the potential environmental impacts is presented.

The mussel culture sub-sector involves the potential impacts linked to the farming of 100 kg of mussels of commercial size. Fresh mussel sub-sector includes the potential impacts associated with the processing of 40 kg of mussels of commercial size in dispatch centres, the household consumption of 32.79 kg of fresh mussels, and the treatment of 0.29 kg of mussel organic waste. The sub-sector of canning factories comprises the processing of 35 kg of mussels of commercial size, the household consumption of 2.76 kg of canned mussel flesh, the treatment of 11.83 kg of mussel shell, and the management of 1.85 kg of mussel organic remains. Finally, the sub-sector of cooking plants considers the boiling and freezing of 20 kg of mussels of commercial size, the boiling and canning of 5 kg of mussels of commercial size, the household consumption of 1.58 kg of frozen boiled mussel flesh and 0.30 kg of canned mussel flesh, the management of 8.44 kg of mussel shell, and the treatment of 0.76 kg of mussel organic waste.

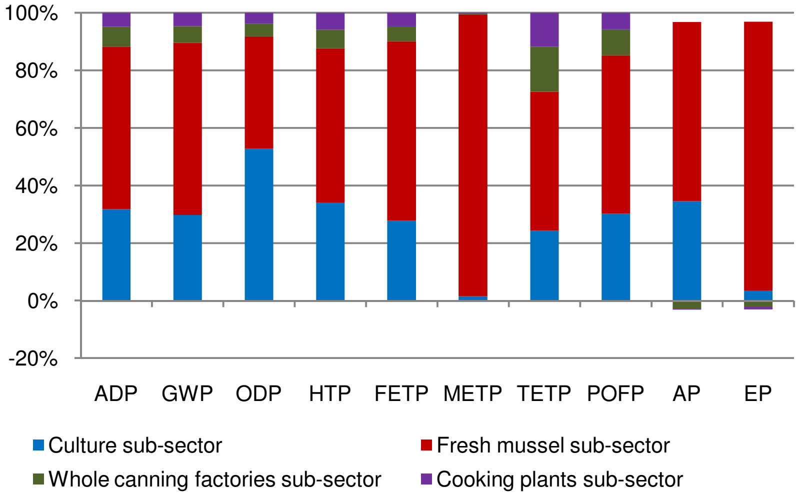

Figure 4.9. *Contributions to the potential environmental impact by the different mussel sub-sectors*

Except for ODP, Figure 4.9 reveals that the sub-sector linked to fresh mussels (dispatch centres) prevailed for all impact categories, especially for METP and EP. For ODP, culture was the sub-sector with the greatest contribution. In fact, mussel farming sub-sector was the second main contributor to the rest of categories. With regard to the sub-sectors of mussel cooking plants and canning factories, their contribution was much lower than that of the other two sub-sectors. This observation is closely related to the high level of optimization for the operations performed in cooking and canning facilities, especially when compared to the unsustainable operation in dispatch centres (traditional family business). Furthermore, the potentially favourable environmental contributions (desirable effects) observed for AP and EP in the case of the cooking and canning sub-sectors are due to the assumption of avoided burdens regarding mussel pâté production (mussel organic waste treatment).

The environmental characterization for the mussel sector led to the conclusion that fresh mussels are the most critical branch within this sector because of the outdated operation performance in dispatch centres. Specifically, the hot spot where improvement actions should be performed is the electricity consumption.

As stated above, new electrical systems with frequency inverters should be adopted.

It could be thought that the environmental relevance of the fresh mussel sub-sector is due to the fact that 40% of the mussels from aquaculture are sent to dispatch centres. In this sense, the following comparative LCA for mussel products helps to refute this idea.

4.4.3. Environmental comparison among mussel-based products

A comparative LCA was carried out in order to compare fresh, canned and frozen mussels on the basis of an equitable functional unit. With this purpose, Table 4.9 compares the characterization values for the potential environmental impacts associated with these three mussel products by taking as functional unit the same protein supply: 8.385 g. This value corresponds to the amount of proteins supplied by either the consumption of one can of mussels (43.00 g of mussel flesh) (Isabel 2009) or the consumption of 322.50 g of fresh mussels (shell and water also included in this final weight) (Consello Regulador 2009) or the consumption of 49.09 g of frozen mussel flesh (Paquito 2009).

In Table 4.9, the term fresh mussels (FM) involved the joint consideration of culture, purification (mussel organic waste management included) and household consumption, whereas the term canned mussels (CM) included cultivation, mussel transformation in canning factories (87.50% processed in whole canning factories and 12.50% in partial ones; treatment of mussel shell and organic waste included) and household consumption. Finally, the term frozen-boiled mussels (FBM) embraced farming, mussel transformation in cooking-freezing facilities (management of mussel shell and organic waste included) and household consumption.

From the ratios FBM/CM gathered in Table 4.9, a similar environmental performance is reported for canned and frozen mussels. On the other hand, the highest potential environmental impact is noted for fresh mussels since all impact categories presented a greater characterization value than those corresponding to canned and frozen mussels.

From inventory data, 322.50 g of fresh mussels imply the farming of 393 g of mussels, while 43.00 g of canned mussel flesh involve the cultivation of 545 g of mussels; and 49.09 g of frozen mussel flesh mean the culture of 622 g of mussels. Moreover, it has been proved that household consumption has little influence on the potential environmental impact. Therefore, the higher potential environmental impact for fresh mussels is linked to mussel purification but not to mussel culture or consumption.

Table 4.9. *Environmental comparison among mussel products on the basis of an equal supply of proteins*

	Fresh mussels (FM)	**Canned mussels (CM)**	**Frozen-boiled mussels (FBM)**	**Ratio FBM/CM**	**Ratio FM/FBM**
ADP (kg Sb eq)	$0.85 \cdot 10^{-2}$	$0.37 \cdot 10^{-2}$	$0.39 \cdot 10^{-2}$	1.05	2.19
GWP (kg CO_2 eq)	1.12	0.42	0.47	1.10	2.40
ODP (kg CFC-11 eq)	$1.09 \cdot 10^{-7}$	$7.05 \cdot 10^{-8}$	$7.62 \cdot 10^{-8}$	1.08	1.44
HTP (kg 1,4-DB eq)	0.24	0.11	0.13	1.15	1.88
FETP (kg 1,4-DB eq)	$8.77 \cdot 10^{-2}$	$2.97 \cdot 10^{-2}$	$3.49 \cdot 10^{-2}$	1.17	2.51
METP (kg 1,4-DB eq)	5,886.57	79.92	86.81	1.09	67.81
TETP (kg 1,4-DB eq)	$0.25 \cdot 10^{-2}$	$0.17 \cdot 10^{-2}$	$0.19 \cdot 10^{-2}$	1.12	1.30
POFP (kg C_2H_4 eq)	$0.04 \cdot 10^{-2}$	$0.02 \cdot 10^{-2}$	$0.02 \cdot 10^{-2}$	1.00	2.07
AP (kg SO_2 eq)	$1.02 \cdot 10^{-2}$	$0.21 \cdot 10^{-2}$	$0.29 \cdot 10^{-2}$	1.40	3.51
EP (kg PO_4^{3-} eq)	$1.00 \cdot 10^{-2}$	$-0.01 \cdot 10^{-2}$	$-3.04 \cdot 10^{-5}$	0.24	-328.94

Where the FU chosen for this comparative study was 1 kg of dry edible mussel flesh, then similar conclusions would be drawn. In such case, the highest potential environmental impact would also be for fresh mussels given that all impact categories would present a greater characterization value than those for canned and frozen mussels, apart from TETP and ODP.

4.5. Conclusions, recommendations and perspectives

LCA has been proved to be suitable when pursuing transparency and accountability all along the trade chain for mussels. Inventories were made for fresh/canned/frozen mussel processing and consumption. These inventories complement that one for mussel culture presented in the previous chapter.

Moreover, the identification of hot spots allowed the proposal of several improvement potentials concerning each of the mussel products. The need to minimize electricity use in dispatch centres is especially highlighted. The installation of modern electric systems provided with frequency inverters is highly encouraged within these facilities. Additional improvement actions should also affect mussel farming.

Furthermore, the LCA of the whole mussel sector revealed that fresh mussel sub-sector was the most contributing one when capturing the real market scenario for mussels. On the contrary, the sub-sectors of mussel cooking plants and canning factories were proved to have a lower contribution to the potential environmental impacts compared to the contribution of culture and dispatch centres sub-sectors.

Finally, a comparison among fresh, canned and frozen mussels was performed, and based on the supply of an identical amount of proteins. Consequently, fresh mussels were found to be the mussel product with the least favourable environmental profile. This higher potential environmental impact is closely related to mussel purification.

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Chapter 5

Environmental assessment of mussel waste valorization[1]

Summary

The evaluation of the treatment of specific mussel wastes is a relevant issue when pursuing a comprehensive study of the mussel sector. In this sense, LCA methodology was used in order to characterize (i) mussel shell valorization to produce calcium carbonate, and (ii) mussel organic waste valorization to produce pâté.

In the first case, propane and electricity use, sludge and ash management, haulage and atmospheric releases were identified as the hot spots on which the improvement potentials should be focused. Furthermore, the environmental assessment of a future scenario for this valorization process is included.

On the other hand, the environmental characterization of mussel organic waste valorization led to the recommendation of acting on the formulation of mussel pâté, the thermal energy demand and the product transport.

Finally, the role of these treatment alternatives when implemented into the case study of mussels is discussed. Mussel waste management was found to contribute to the potential environmental impacts to a lesser extent than mussel culture and processing.

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[1] Iribarren, D., Moreira, M.T., Feijoo, G. (2010). “Implementing by-product management into the Life Cycle Assessment of the mussel sector”. Resour Conserv Recy. DOI: 10.1016/j.resconrec.2010.03.017

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5.1. Introduction

The Galician mussel sector does not focus only on cultivation, but also comprises other activities such as those performed by dispatch centres, cooking plants and canning factories (Franco 2006). All these processing activities generate several waste streams which have to be managed. In this context, the management of two specific mussel waste materials should be highlighted:

- Management of mussel shells and other mussel debris mainly from canning factories and, to a lesser extent, from cooking plants and dispatch centres. The most popular management option for these waste materials is their valorization to obtain calcium carbonate (Barros et al. 2009a).
- Management of mussel organic waste from canning factories, cooking plants and dispatch centres. This type of waste can be sent to factories that produce fish meal. However, the production of mussel pâté from mussel organic waste is currently a valorization alternative gaining increasing popularity.

In this chapter, LCA is used to assess the environmental performance of these management options. This study meets the need for the implementation of the management of mussel shell and organic wastes from processing factories into the target life cycle of the mussel case study.

5.2. Methods

The goal of this chapter is to perform a detailed environmental assessment of the waste management systems S6 (i.e., mussel shell management) and S7 (i.e., mussel organic waste management) by means of LCA methodology. Remember that nomenclature is in accordance with Figure 3.1 in Chapter 3.

First, the LCA for mussel shell management is posed. The term shell stands for both the mussel shell itself and other valorizable mussel debris. Mussel shell comes mainly from system S3 (canning factories), and is valorized to obtain $CaCO_3$. The aim is to environmentally assess this valorization process by characterizing system S6, identifying the corresponding hot spots and proposing several improvement potentials.

Second, the LCA for mussel organic waste management is tackled. Mussel organic waste refers to small mussel meat remains which are discarded in the course of mussel processing. This waste comes from systems S2 (dispatch centres), S3 (canning factories), S4 (cooking plants) and S5 (partial canning factories), and is managed by manufacturing mussel pâté. The objective is to carry out the environmental assessment of this process by means of the characterization of system S7, the detection of hot spots and the proposal of improvement potentials.

The final objective seeks to show the implementation of S6 and S7 into the general mussel case study.

5.2.1. System boundaries

Mussel shell valorization

With the aim of assessing mussel shell valorization to produce calcium carbonate (Calizas Marinas 2009), system S6 was divided into five subsystems as shown in Figure 5.1.

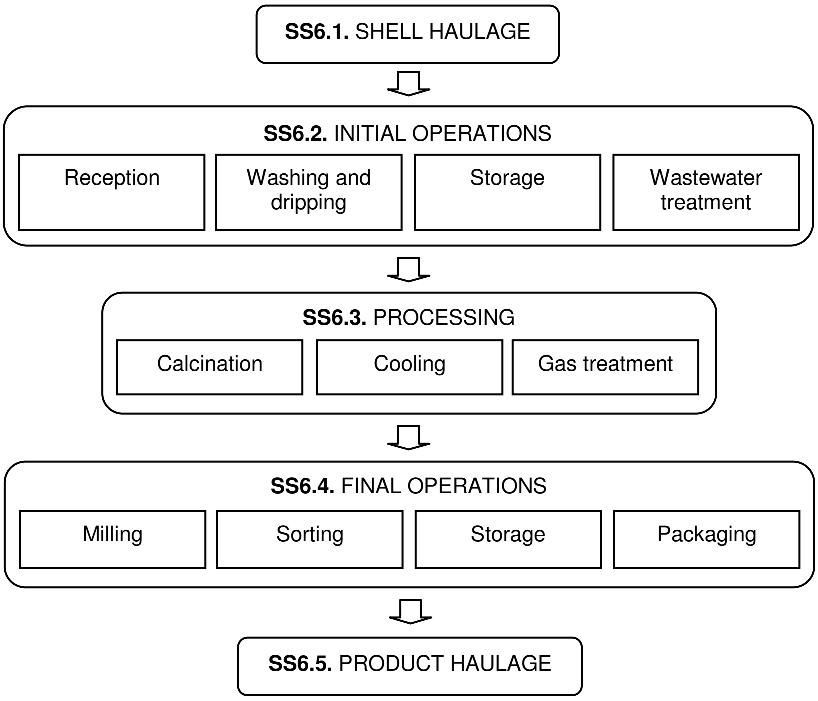

Figure 5.1. *Subsystems for mussel shell management (S6): calcium carbonate production*

Subsystem SS6.1 (shell haulage) just comprises the initial haulage of the shell from its origin (mainly canning factories) to the valorization plant.

Subsystem SS6.2 (initial operations) includes: (i) reception and storage, (ii) washing and dripping, (iii) storage, and (iv) wastewater treatment. Mussel shells are transported by truck to the valorization facility. These trucks unload mussel shells inside two reception hoppers. Afterwards, mussel shells are washed with fresh water in order to reduce the salt content of the final product, avoiding the wear of the equipment because of corrosion and obtaining concentrated $CaCO_3$. This subsystem demands large amounts of water. Washing is carried out in two rotary washing machines with counter-current operation to perform the salt extraction. The next step consists of a shaker draining rack that removes the water dragged by the product. Wastewater and mud waste are channelled to the on-site wastewater treatment plant. The washed material completes its dripping in five stainless steel silos where the washed shell is stored for a maximum of three days. Leachates are also sent to the wastewater treatment plant.

Subsystem SS6.3 (processing) covers: (i) calcination, (ii) cooling, and (iii) gas treatment. In this sense, the processing subsystem involves the thermal treatment of mussel shells, the subsequent cooling of the dead burned material and the exhaust gas treatment (Barros et al. 2007). Calcination takes place in a rotary kiln where drying and calcining operations take place. Drying is performed at 190ºC for 18 min, whereas calcination is carried out at 550ºC for 15 min. Afterwards, the cooling process is developed in two steps. Firstly, a thinly dispersed water injection achieves a temperature of 200ºC, followed by air refrigeration reducing the final temperature to 60ºC. The exhaust gas treatment is performed by means of a bag house filter and a regenerative thermal oxidizer.

Subsystem SS6.4 (final operations) consists of: (i) milling, (ii) sorting, (iii) storage, and (iv) packaging. These final operations prepare the final products for the marketing process. As the material is cooled, a screw moves it forward to a bucket-conveyor belt that feeds the milling equipment. Therefore, once cooled to a temperature below 60ºC and moisture-free, the calcined shell advances to the milling unit with the aim of crushing the shell to obtain different grain sizes, providing a suitable granulometry for the product according to market requirements. Several products with purity levels of 90-95% in $CaCO_3$ and different particle sizes are obtained in order to satisfy different industrial applications. The sorted fractions of the final products are stored in three hoppers according to the grain size. Then, the products can be stored either in two enclosed warehouses or in silos depending on the final use and the packaging format. The final products are packaged in bulk (tanks or containers) or big bags (capacity for 1 m^3).

Finally, subsystem SS6.5 (product haulage) includes the final haulage of the commercial $CaCO_3$ products.

Mussel organic waste valorization

For the environmental assessment of mussel pâté production from mussel organic waste, system S7 was studied by means of an analogy with tuna pâté production (Grupo Calvo 2009). As observed in Figure 5.2, pâté production involves several key stages.

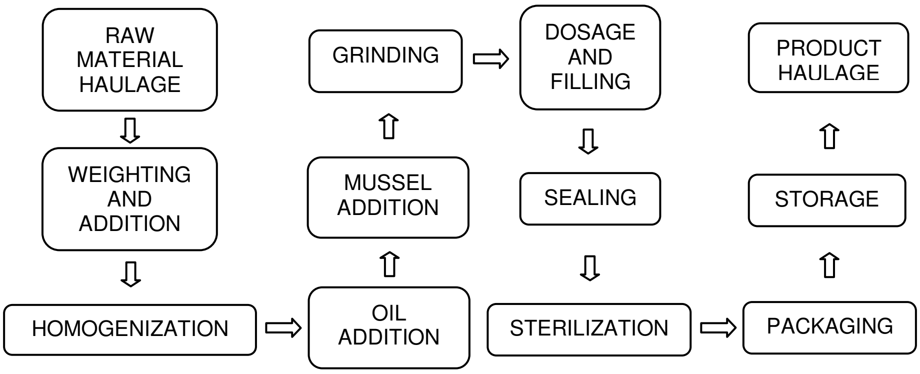

Figure 5.2. *Operations considered within the system boundaries for pâté production*

Initially, raw materials are transported to the factory. Then, water is weighed and added to the cutter machine (mixer). Afterwards, dry ingredients are also weighed and added. The following step is to mix the blend until the paste presents a shiny appearance without lumps. The paste is left to settle in order to achieve a complete hydration of the soya protein which has been previously used as an ingredient. The next stages consist in the addition of oil and mussel organic waste. If part of the mussel input arrives to the factory as a non-boiled input, a cooking stage is needed before mussel addition. After a few minutes of grinding, the resulting paste (pâté) is transferred to a filling machine. Once this step is achieved, the product is ready for sealing and sterilization. The final product is packaged, stored and, finally, transported for its commercialization. All these processes were considered within the system boundaries of S7, and they were jointly studied (i.e., just one inventory was required for S7).

5.2.2. Functional unit

Mussel shell valorization

The FU for S6 was 100 tonnes of mussel shell waste for valorization. This choice involves the production of 65 tonnes of $CaCO_3$ products (Calizas Marinas 2009).

Mussel organic waste valorization

The FU for S7 was 100 tonnes of mussel organic waste for mussel pâté production. This FU entails the manufacture of 278 tonnes of mussel pâté (Grupo Calvo 2009).

Comparison with other management options

The comparisons established among the target management solutions and other alternatives are made on the basis of the same amount of waste for management (100 tonnes).

Implementation into the mussel case study

The discussion concerning the implementation of S6 into the mussel case study is presented for the management of 100 tonnes of mussel shell waste, including the potential impacts linked to the origin of this mussel shell waste. An analogous integration is raised for the management of 100 tonnes of mussel organic waste (S7).

5.2.3. Data acquisition

Mussel shell valorization

For mussel shell valorization, data were taken from a Galician factory which annually manages more than 18,000 tonnes of mussel shell waste. The valorization of this waste gives rise to more than 12,000 tonnes of $CaCO_3$ products. An exhaustive study of input and output streams was carried out. Furthermore, internal reports involving analyses for wastewater and atmospheric emissions were used as well as information related to the haulage of raw materials and products.

Mussel organic waste valorization

Data for mussel organic waste valorization were obtained in collaboration with a Galician tuna pâté factory which annually produces around 280 tonnes of pâté. This allowed drawing an analogy for mussel pâté production. In this sense, the production of 100 tonnes of pâté means the management of 36 tonnes of mussel organic waste. The corresponding input and output streams were studied in depth.

General considerations and assumptions

Allocation may be necessary when multifunctional processes are involved. In the case of mussel by-product valorization, 100% of the environmental burdens are initially imposed to the corresponding waste flows entering S6 and S7: mussel shells and mussel organic wastes, respectively. Nevertheless, it is possible to adopt an avoided burdens approach since valorization provides commercial products.

This chapter focuses on two valorization systems: mussel shell management to produce calcium carbonate, and mussel organic waste management to produce pâté. Therefore, these systems do not simply offer a waste management service (unlike landfilling) but also arise as manufacturers. In other words, commercial products are made from the mussel waste (by-product) streams. These products are then introduced in the market so they satisfy a certain part of the product market demand. In this context, products from valorization are said to avoid the conventional production of the goods being replaced. Consequently, the environmental burdens associated with the conventional processes are also avoided. Thus, it is possible to subtract such burdens from those corresponding to waste management. This is the concept of avoided burdens in LCA, which is not a procedure lacking in discussion because of ambiguity concerns (Heijungs & Guinée 2007). In section 5.4, the relevance of this approach is studied for mussel waste valorization.

On the other hand, if environmental burdens were allocated to the commercial products from valorization, then product allocation could be necessary for the different $CaCO_3$ products from mussel shell valorization (allocation factors suggested in Table 5.1). However, this is not the case for the current study.

Table 5.1. *Economic and mass allocation factors for mussel shell valorization*

Final product	Amount (t)	Price (€/t)	€	Economic allocation factor (%)	Mass allocation factor (%)
Middle $CaCO_3$	3	16.50	49.50	3.25	4.62
Fine $CaCO_3$	10	16.50	165.00	10.84	15.38
Micronized $CaCO_3$	24	30.00	720.00	47.29	36.92
$CaCO_3$ + sawdust	28	21.00	588.00	38.62	43.08

For both S6 and S7, the quantification of capital goods is avoided (Renou et al. 2008) on the basis of the long life estimated for the installations (more than 20 years in both cases).

Electricity production corresponds to the electricity production mix for Spain as presented in the ecoinvent database (Dones et al. 2007). This assumption is thought to be the most accurate approach for this specific case study.

In order to clarify the study of the relevance of the environmental performance of S6 (shell valorization) when implemented into the general case study, canning factories (S3) are assumed to be the only source of shell waste. Therefore, this implementation just involves systems S1, S3, S6 and S7.

Finally, the integration of S7 (mussel organic waste valorization) into the general case study is carried out assuming that 91.75% of the mussel organic waste comes from canning factories (S3) and the remaining part from dispatch centres (S2). These percentages are obtained from the inventory data available for S2 and S3 (gathered in Chapter 4), taking into account that 40% of farmed mussels are assigned for fresh consumption (Xunta de Galicia 2006). Hence, this implementation affects systems S1, S2, S3, S6 and S7.

5.2.4. Life cycle inventory

Mussel shell valorization

As previously stated, it was necessary to analyze the input/output flows of a Galician factory with the purpose of inventorying mussel shell valorization. This exhaustive study led to partial inventories for the five subsystems defined for mussel shell valorization. These inventories are presented in Table 5.2a-e.

Table 5.2a. *Inventory data for mussel shell valorization: SS6.1*

INPUTS			OUTPUTS		
From the technosphere			**To the technosphere**		
Transport			**Product**		
1. Shell up to the factory	216.33	km	1. Transported mussel shell and debris	100.00	t
Material					
1. Mussel shell	55.56	t			
2. Mussel debris	44.44	t			

Table 5.2b. *Inventory data for mussel shell valorization: SS6.2*

INPUTS			OUTPUTS		
From the technosphere			**To the technosphere**		
Materials			**Product**		
1. Chemicals and other materials			1. Washed and dripped shell	95.00	t
Coagulant	55.00	l	**Waste to treatment**		
DAF flocculant	6.00	kg	1. Sludge	2.50	t
Flocculant	7.50	l	**To the environment**		
2. Raw materials			**Emissions to the ocean**		
Transported mussel and debris	100.00	t	1. COD	8.81	kg O_2
3. Water			2. BOD_5	0.19	kg O_2
Fresh water	60.00	m^3	3. Suspended solids	1.56	kg
Energy			4. Organic nitrogen	0.46	kg
1. Electric energy	5,100.00	kWh	5. Ammoniacal nitrogen	0.05	kg
			6. Fats	0.62	kg
			7. Phosphates	0.06	kg
			8. Nitrates	0.26	kg

Table 5.2c. *Inventory data for mussel shell valorization: SS6.3*

INPUTS			OUTPUTS		
From the technosphere			**To the technosphere**		
Materials			**Product**		
1. Chemicals and other materials			1. Calcined shell	60.00	t
Propane	2.10	t	**Waste to treatment**		
Antifouling	0.70	l	1. Ashes	2.00	t
Biocide	0.70	l	**To the environment**		
2. Raw materials			**Emissions to the atmosphere**		
Washed and dripped shell	95.00	t	1. Water	35.00	t
3. Water			2. Air	135,520.00	m^3
Cooling water	35.00	m^3	3. NH_3	0.22	kg
Energy			4. Particles	0.65	kg
1. Electric energy	5,300.00	kWh	5. SO_2	3.01	kg
			6. NO_x	32.28	kg NO_2
			7. CO_2	6,020.00	m^3
			8. O_2	35,905.00	m^3
			9. CO	21.95	kg

Table 5.2d. *Inventory data for mussel shell valorization: SS6.4*

INPUTS			OUTPUTS		
From the technosphere			**To the technosphere**		
Materials			**Products**		
1. Chemicals and other materials			1. Middle $CaCO_3$	3.00	t
Diesel oil	57.00	l	2. Fine $CaCO_3$	10.00	t
Polypropylene big-bags	17.00	units	3. Micronized $CaCO_3$	24.00	t
2. Raw materials			4. $CaCO_3$ + sawdust	28.00	t
Calcined shell	60.00	t			
Sawdust	5.00	t			
Energy					
1. Electric energy	5,700.00	kWh			

Table 5.2e. *Inventory data for mussel shell valorization: SS6.5*

INPUTS			OUTPUTS		
From the technosphere			**To the technosphere**		
Transport			**Product**		
1. Products up to destination	299.67	km	1. Transported $CaCO_3$	100.00	t
Material					
1. Middle $CaCO_3$	3.00	t			
2. Fine $CaCO_3$	10.00	t			
3. Micronized $CaCO_3$	24.00	t			
4. $CaCO_3$ + sawdust	28.00	t			

Mussel organic waste valorization

Inventory data for mussel meat waste valorization were obtained from the thorough analysis of a Galician factory which produces pâté. Table 5.3 presents the inventory for S7.

Table 5.3. *Inventory data for mussel organic waste valorization*

INPUTS FROM THE TECHNOSPHERE					
Materials			**Materials**		
1. Raw materials			4. Containers		
Mussel organic waste[a]	100.00	t	Cans (tinplate)	91.34	t
Water	111.83	t	Cardboard	15.13	t
Oil	23.61	t	Film (LDPE)	2.28	t
Egg albumen	6.94	t	**Energy**		
Skimmed milk powder	5.56	t	1. Electric energy	60,147.60	kWh
Starch	2.78	t	2. Thermal energy	850,458.29	MJ
Salt	2.78	t	**Transport**		
Soya protein	2.78	t	1. Mussel organic waste	10,820.00	t·km
Aromas and spices	15.28	t	2. Other raw materials	78,624.32	t·km
2. Chemicals and other materials			3. Cans	107,913.84	t·km
Flocculant	6.00	kg	4. Cardboard	1,701.26	t·km
Coagulant	3.05	kg	5. Film	270.99	t·km
3. Fresh water	1,886.03	m^3	6. Flocculant	2.78	t·km
			7. Coagulant	1.30	t·km
			8. Product (mussel pâté)	180,063.48	t·km

[a] 44% of the mussel organic waste enters the process as a boiled input, and 56% enters as a non-boiled input. Specifically, 44.12 boiled tonnes come from canning factories, 44.12 non-boiled tonnes come from canning factories, and 11.76 non-boiled tonnes arrive from dispatch centres

Table 5.3. *Inventory data for mussel organic waste valorization (cont.)*

OUTPUTS					
To the technosphere			**To the environment**		
Product			**Emissions to the ocean**		
1. Mussel pâté	277.79	t	1. Treated wastewater	1,312.56	m^3
Waste to treatment			COD	170.63	kg O_2
1. Cardboard to recycling	0.81	t	Nitrates	0.66	kg
2. Film to recycling	0.48	t	**Emissions to the atmosphere**		
3. Residual cans (tinplate)	0.43	t	1. CO_2	306.87	kg
4. Sludge	0.40	t	2. CH_4	590.13	kg
			3. CO	1.89	kg
			4. N_2	28.33	kg
			5. H_2	14.16	kg
			6. H_2S	2.83	kg

5.3. Results

As in the previous chapters, SimaPro 7 was the software used for the computational implementation of the inventories (Goedkoop et al. 2008). The ecoinvent database was chosen for background processes, just resorting to ETH ESU 96 database (e.g. for the landfill management of the sludge from SS6.2 and S7, or for the consideration of sawdust as wood waste in forest for SS6.4), BUWAL 250 database (e.g. for cans in S7) and LCA Food data base (e.g. data adapted for milk powder in S7) when necessary.

Classification and characterization following ISO guidelines were performed to evaluate the potential environmental impact of inputs and outputs from the LCIs. The CML method was used. AP, ODP, ADP, GWP, EP, POFP, FETP, METP, TETP and HTP were the impact categories evaluated.

5.3.1. Mussel shell valorization

The characterization results for mussel shell valorization (S6) are presented in Figure 5.3, which clearly illustrates the contribution of the five subsystems to the ten impact categories.

Shell haulage (SS6.1) showed contributions ranging from 1% to 7%, whereas the corresponding contribution ranges for initial operations (SS6.2), processing (SS6.3), final operations (SS6.4) and products haulage (SS6.5) were 12-89%, 5-73%, 2-37% and 2-17%, respectively.

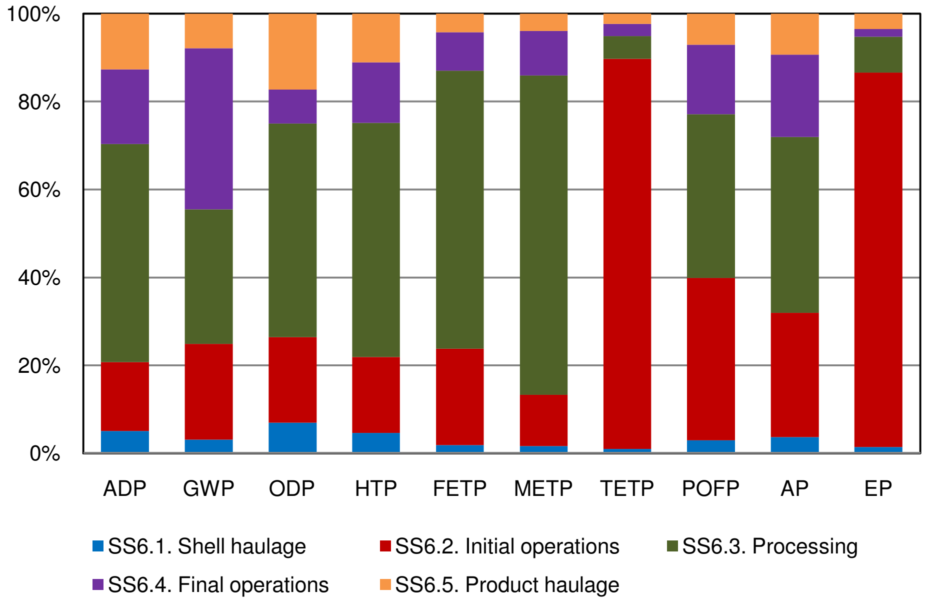

Figure 5.3. *Subsystem contribution to the environmental impact potentials for mussel shell valorization (S6)*

Furthermore, the following processes were broken down for mussel shell valorization: initial haulage of mussel shell and debris for SS6.1; water supply for SS6.2 and SS6.3; coagulant and flocculant production for SS6.2; electricity production for SS6.2, SS6.3 and SS6.4; sludge management within initial operations (SS6.2); water discharge in SS6.2; propane production as well as anti-fouling agent and biocide production for SS6.3; atmospheric emission concerning SS6.3; ash management regarding processing (SS6.3); diesel oil, sawdust and big-bag production for final operations (SS6.4); and the final haulage of the $CaCO_3$ products for SS6.5.

The main processes contributing to the potential environmental impacts are summarized in Figure 5.4, where a simplified contribution diagram is presented for mussel shell valorization (simplified contribution diagram for processes with a contribution greater than 1%).

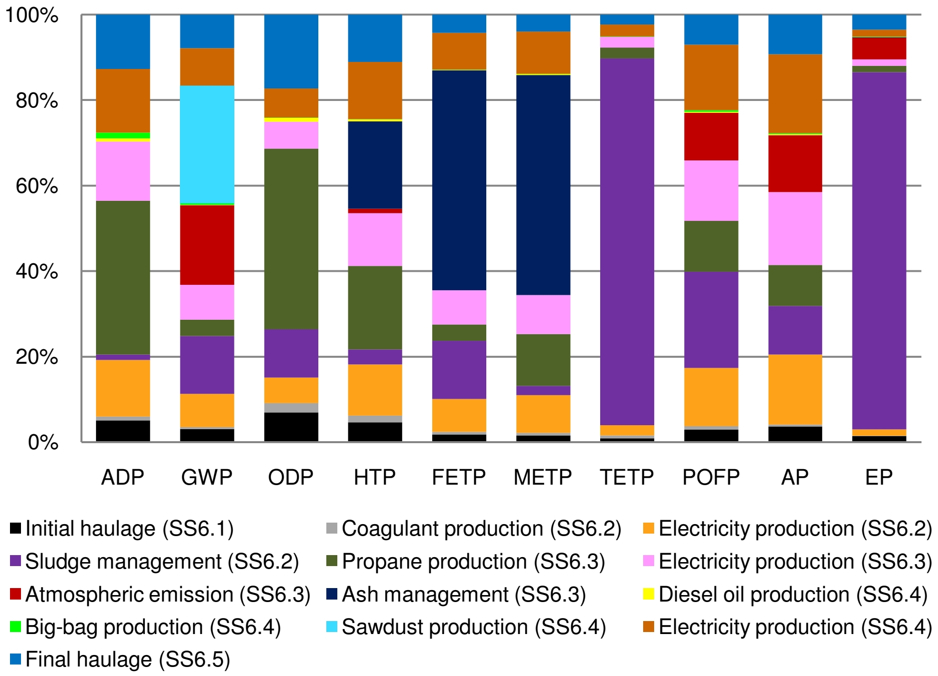

Figure 5.4. *Process contribution for mussel shell valorization (S6)*

As observed in Figure 5.4, propane production for processing arose as the main process contributing to ADP (36% of the total impact for this category) and ODP (42%). This process also involved relevant contributions to POFP (12%), AP (10%), HTP (20%) and METP (12%).

Electricity production played a role in every impact category. Specifically, electricity production for final operations was found to be the main contributor to AP with 18% of the total impact for this category, ahead of electricity production for processing (17%) and electricity production for preliminary operations (16%). Electricity production for each of the subsystems (SS3.4, SS3.3 and SS3.2) also showed relevant contributions to POFP, ADP, GWP, ODP, HTP, FETP and METP, with percentages around 10% in every case.

For GWP, sawdust production emerged as the main contributor. However, this contribution could be omitted since the company states that sawdust is originally a waste stream. Consequently, no emission should be allocated to sawdust, and it could be included as an empty process. Therefore, atmospheric emission within processing subsystem would become the real main contributor to GWP. In fact, it also involved relevant contributions to POFP (11% of the total impact for this category), AP (13%) and EP (5%).

Sludge management was found as the main process contributing to POFP (22% of the total impact for this category), EP (83%) and TETP (86%). This process also contributed significantly to GWP (>10%), ODP (11%), AP (11%), HTP (4%) and FETP (13%).

On the other hand, ash management was the process leading the potential contribution to three impact categories: HTP (20% of the total impact for this category), FETP (51%) and METP (51%).

None of the haulage processes was found as the main contributor for any impact category. Nevertheless, haulage involved significant contributions to ADP, GWP, ODP, POFP, AP and HTP. Final haulage showed contribution percentages more than twice the percentages related to initial haulage.

Finally, to a lesser extent, other processes contributed to the potential environmental impacts. For example, coagulant production accounted for a contribution of 2% to ODP and HTP.

5.3.2. Mussel organic waste valorization

With regard to the environmental characterization of mussel organic waste valorization, the following processes were included: input transport, water supply as an ingredient, production of each of the ingredients (oil, egg albumen, skimmed milk powder, starch, salt, soya protein, aromas and spices), flocculant production, coagulant production, can production, cardboard production, packaging film production, additional water supply, electric energy production, thermal energy production, cardboard recycling, film recycling, tinplate management, sludge management, emissions to the environment, and product transport.

The main processes contributing to the potential environmental impacts associated with mussel organic waste valorization are summarized in Figure 5.5 (simplified contribution diagram for processes with a contribution greater than 5%). It is observed that thermal energy production and raw material production were the key processes concerning potential environmental impacts.

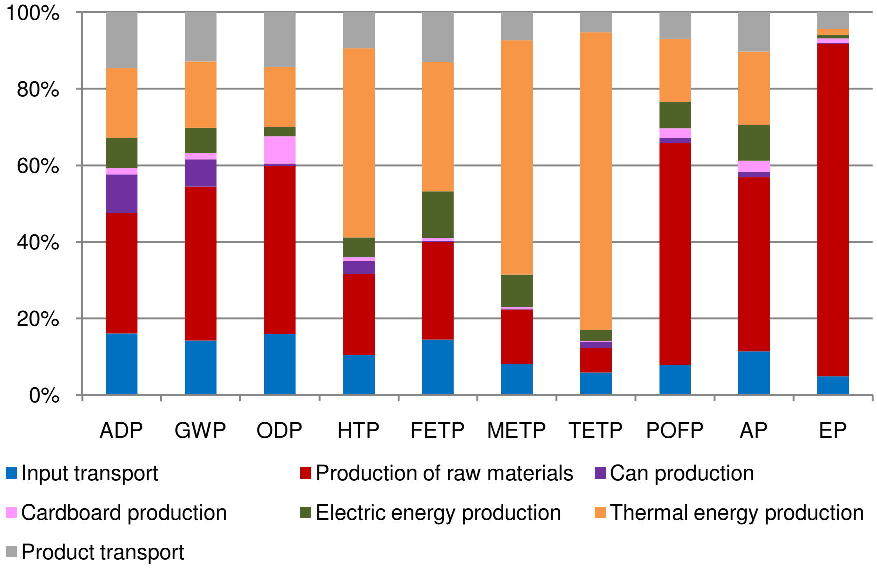

Figure 5.5. *Process contribution for mussel organic waste valorization*

Thermal energy production is linked to the thermal energy demand for (i) the cooking of non-boiled mussel organic waste, and (ii) the sterilization of cans. This process prevailed for the contribution to the toxicity and eco-toxicity categories, with 49% of the total impact for HTP, 33% for FETP, 61% for METP and 76% for TETP. Furthermore, thermal energy production presented relevant contribution percentages for AP (19%), ADP (18%), GWP (17%), POFP (16%) and ODP (15%).

The term production of raw materials includes the production process for each of the ingredients (oil, egg albumen, skimmed milk powder, etc.). This set of processes accounted for the greatest contributions to EP (86% of the total impact for this category), POFP (56%), AP (45%), ODP (43%), GWP (39%) and ADP (30%). In particular, the contributions to EP and AP were mainly related to oil, egg albumen and skimmed milk powder production. Oil production and the production of aromas and spices were found to prevail for ADP. These processes along with skimmed milk powder production were the main sources for GWP and ODP. Finally, the contribution to POFP was mainly associated with the production of aromas and spices, as well as to the production of oil and soya protein. Raw material production also showed relevant contribution percentages for the toxicity and eco-toxicity categories, mainly due to the production of aromas and spices.

Transport also played a role in the potential environmental impacts for S7. The transport related to inputs involved contribution percentages ranging from 5% (for EP) to 16% (for ADP), mainly due to the haulage of raw materials (ingredients) and cans. On the other hand, product haulage (mussel pâté transport) accounted for contributions ranging from 4% (for EP) to 14% (for ADP).

Other processes should not be disregarded. For instance, the environmental impact contributions of electricity production ranged from 1% (for EP) to 12% (FETP). Can production also showed some relevant contributions to the potential environmental impacts, especially to ADP (10% of the total impact for this category) and GWP (7%). Note that the contributions associated with can production are strongly influenced by the chosen database. Another process related to the packaging format is cardboard production, which accounted for 7% of the total impact for ODP. To a lesser extent, emissions to air contributed to 3% of the total impact for GWP and to 2% for POFP. Similarly, packaging film production accounted for 3% of the total impact for ADP and for 1% of the impact for FETP and GWP. Flocculant production gave rise to 3% of the total impact for ODP. Finally, sludge management contributed to 1% of the impact for TETP.

5.4. Discussion and identification of improvement potentials

5.4.1. Mussel shell management

From the environmental characterization of mussel shell valorization (S6), the corresponding hot spots were identified. These included (i) propane production for processing, (ii) sludge management, (iii) ash management, (iv) electricity production for final operations, processing and final operations, (v) initial and final haulage, and (vi) atmospheric emission linked to processing. On the basis of these remarks, the corresponding improvement potentials should be focused on the:

- Minimization of propane consumption or proposal and evaluation of new alternatives. Actions should be taken in the calcination process and in gas treatment.

- Use of processing ashes due to their high $CaCO_3$ content, and further research on sludge valorization.
- Optimization of the electricity demand for final operations, processing and preliminary operations.
- Logistical planning, especially for the final haulage of $CaCO_3$ products, but also for the initial haulage of raw materials.

With the aim of dealing with system S6 in depth, a future scenario is presented for mussel shell valorization. This scenario was based on true trends according to personal communications from the valorization company. It included three hypothetical improvement actions of environmental and economic interest:

- Use of glycerine instead of propane for the calcination process in SS6.3. In order to implement this alternative, it was necessary to determine the glycerine and propane needs along with the corresponding atmospheric emissions. This was made from internal reports of the mussel shell waste valorization plant and other sources dealing with glycerine combustion (Metzger 2007; Patzer 2007; Aqua-Fuel Research 2008; Bluer 2008). It should be stressed that the management of 100 tonnes of mussel shell waste would involve the use of 13.40 tonnes of glycerine; furthermore, 227 kg of propane would be needed for pre-combustion.
- Assumption of 100% of the processing ashes as a sub-product instead of as a waste stream. Currently, the entire ash production is managed by disposal to opencast refill. However, according to company reports, these ashes have a high $CaCO_3$ content (80-85%), and this is the reason why their appreciation as a sub-product could be assumed as the equality among the amount of ashes produced and the same amount of $CaCO_3$ as an avoided product (background process from the ecoinvent database).
- Dispatch of 100% of the sludge to its valorization. Currently, the sludge management entails being sent to landfill. However, in the future scenario, the entire sludge production undergoes filtration, settling and dehydrating in order to produce an agricultural fertilizer mainly used for cereal crops, roughly 30% for wheat and barley fields, 68% for meadows and 2% for alfalfa (Camino 2004). On the basis of internal reports, the sludge from preliminary operations (SS6.2) is 70% water. Consequently, with an additional energy supply of 176.57 kWh (ACS 2008), the amount of sludge assigned to valorization (2.5

tonnes according to Table 5.2b) was assumed to avoid the production of 0.75 tonnes of agricultural fertilizer (background process from IDEMAT 2001 database).

The use of LCA methodology in this future scenario for mussel shell waste valorization led to new values regarding its environmental characterization, which are gathered in Table 5.4.

Table 5.4. *Characterization values for current S6 versus those for the future scenario*

	Current S6 after subtraction (O)	Future S6 after subtraction (F)	Ratio O/F
ADP (kg Sb eq)	134.67	289.30	0.47
GWP (kg CO_2 eq)	31,463.05	67,485.05	0.47
ODP (kg CFC-11 eq)	0.0022	0.0040	0.55
HTP (kg 1,4-DB eq)	3,191.97	21,581.86	0.15
FETP (kg 1,4-DB eq)	1,882.68	153,410.85	0.01
METP (kg 1,4-DB eq)	4,386,467.83	5,727,072.71	0.77
TETP (kg 1,4-DB eq)	210.52	68,000.23	0.00
POFP (kg C_2H_4 eq)	6.38	27.43	0.23
AP (kg SO_2 eq)	144.57	419.18	0.34
EP (kg PO_4^{3-} eq)	84.46	210.38	0.40

As presented in Table 5.4, the future characterization values were considerably higher for all impact categories. This entails that the current scenario enjoys a more favourable environmental performance than the future system S6. With the aim of finding the rationale behind this performance, Figure 5.6 shows the subsystem and process contribution to the potential environmental impacts for the future scenario. Hence, processing (SS6.3) was clearly found as the main contributing subsystem, with percentages greater than 74% for all categories. Specifically, glycerine production was the process with the greatest contribution percentages. Actually, ash appreciation and sludge valorization were observed as environmentally friendly measures. However, the future scenario as a whole was not environmentally favourable because of the use of glycerine replacing propane for combustion, which was proved not to be a good alternative, even outshining the benefits of the other improvement potentials.

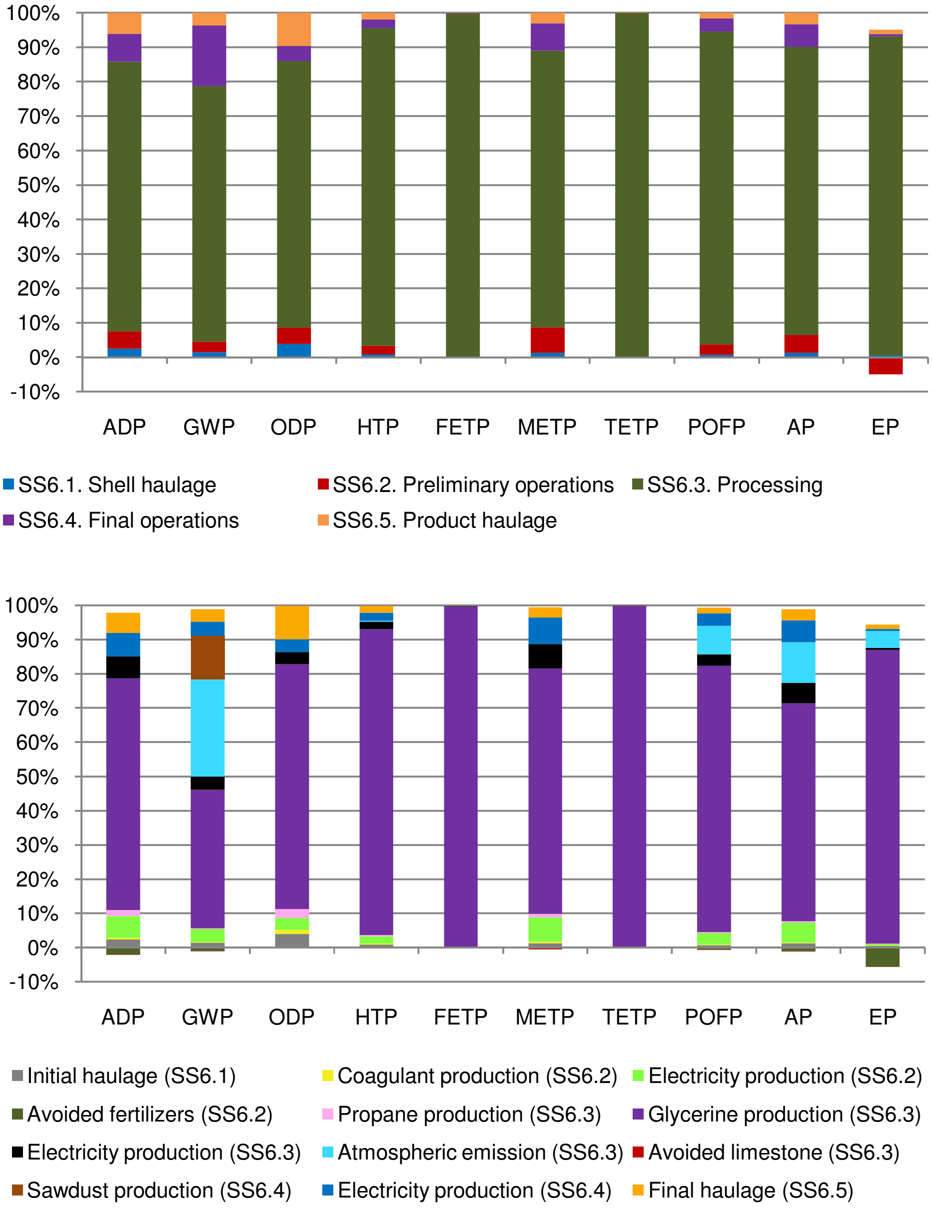

Figure 5.6. *Subsystem and simplified process contribution for the new scenario concerning mussel shell valorization*

Furthermore, the comparison among the current environmental performance of this management option (current S6) and that of other alternatives is also considered. Thus, Table 5.5 gathers the environmental characterization values for several options considered for the management of 100 tonnes of mussel shell waste.

Table 5.5. *Environmental comparison among mussel shell waste valorization and other management options (landfilling and incineration). The environmental impact reduction by avoiding conventional $CaCO_3$ production has been included*

	Current S6 (O)	S6 after subtraction (S)	Landfilling (L)	Incineration (I)	Ratio O/S	Ratio L/S	Ratio I/S
ADP (kg Sb eq)	143.08	134.67	31.82	1,576.74	1.06	0.24	11.71
GWP (kg CO_2 eq)	32,963.11	31,463.05	3,580.18	351,969.60	1.05	0.11	11.19
ODP (kg CFC-11 eq)	$0.23\cdot10^{-2}$	$0.22\cdot10^{-2}$	$0.61\cdot10^{-2}$	0.33	1.07	2.78	152.22
HTP (kg 1,4-DB eq)	3,993.29	3,191.97	1,575.43	57,408.33	1.25	0.49	17.99
FETP (kg 1,4-DB eq)	2,103.11	1,882.68	268.00	14,302.31	1.12	0.14	7.60
METP (kg 1,4-DB eq)	4,903,258.36	4,386,467.83	883,641.59	45,478,944.22	1.12	0.20	10.37
TETP (kg 1,4-DB eq)	216.30	210.52	8.30	435.11	1.03	0.04	2.07
POFP (kg C_2H_4 eq)	6.64	6.38	1.63	31.39	1.04	0.26	4.92
AP (kg SO_2 eq)	150.94	144.57	23.44	505.43	1.04	0.16	3.50
EP (kg PO_4^{3-} eq)	85.82	84.46	3.81	198.34	1.02	0.05	2.35

In Table 5.5, the characterization values for the current S6 (mussel shell valorization to produce $CaCO_3$ products) are compared to those values for mussel shell incineration and mussel shell management in landfill. Moreover, it was taken into account that the production of a certain amount of $CaCO_3$ by means of a waste valorization process avoids obtaining the same amount of calcium carbonate by the conventional process; then it could be asserted that the conventional production of 65 tonnes of $CaCO_3$ is avoided by the valorization of 100 tonnes of mussel shell waste. Nevertheless, from Table 5.5, it is deduced that the environmental characterization values for S6 once subtracted the environmental burdens of the conventional process hardly varied. This is due to the slight potential impact linked to the conventional process. Therefore, the strength of the proposed mussel shell waste valorization should be found from its comparison with other waste management options. In this sense, for the incineration option, the characterization values for all impact categories were much higher than those regarding the valorization system, i.e. mussel shell waste incineration is discouraged. On the contrary, landfilling presented characterization values lower than those for valorization (except for ODP). However, land occupation and social concerns would dramatically complicate the success of this alternative; moreover, landfilling generates no marketable product unlike the valorization option, which is both economically and socially favoured.

5.4.2. Mussel organic waste management

The environmental characterization for mussel organic waste valorization to produce mussel pâté (S7) revealed the following hot spots: (i) production of raw materials, (ii) thermal energy production, and (iii) product transport. According to these observations, the corresponding improvement potentials should be focused on the:

- Optimization of the ingredient ratio. Specifically, a major objective should seek the minimization of the demand of oil, milk, aromas and spices.
- Optimization of the thermal energy demand for the cooking of non-boiled mussel meat remains and the sterilization of cans.
- Logistical planning for the transport of mussel pâté.

Mussel organic waste is sometimes used as an input for fish meal production. In this sense, the assumption made in Chapter 4 for the individual life cycle assessments of fresh/canned/frozen mussels considers that these mussel organic remains are equivalent to the same amount of an avoided product which is the organic input for fish meal production (Nielsen et al. 2003). Note that the avoided product would not be fish meal but the organic input entering the industrial process for fish meal production. Therefore, mussel organic waste would constitute a small fraction of the ingredients for fish meal production. The weakness of this approach lies in the use of non-specific data which do not reliably fit to the case study of the mussel sector. Consequently, in this context, it should be convenient to use system S7 as presented in this chapter (mussel organic waste valorization to produce mussel pâté). Another advantage in favour of mussel pâté production is that mussel organic waste is the key ingredient for mussel pâté production. Furthermore, unlike fish meal, mussel pâté has the advantage of being assigned for direct human consumption.

In the case of mussel shell management, it was argued the fact that the production of $CaCO_3$ by waste valorization avoids obtaining a certain amount of calcium carbonate by the conventional process. Similarly, in the case of mussel organic waste management, mussel pâté could be considered as a replacement of certain foodstuffs for sandwiches (e.g. boiled ham). This assumption helps to reduce the environmental penalty associated with waste treatment. This reduction is especially important when implementing the management of mussel organic waste into the general case of the mussel sector. In this sense, Table 5.6 compares the characterization values obtained for the management of 100 tonnes of mussel organic waste with and without assuming the subtraction of the avoided burdens. For this comparison, it was assumed that 278 tonnes of mussel pâté avoid the production of 192 tonnes of boiled ham on the rationale of a same protein supply for humans (Grupo Calvo 2009).

Table 5.6. *Environmental comparison between mussel organic waste valorization (S7) with and without the assumption of avoided burdens (management of 100 tonnes of mussel organic waste)*

	Current S7 (O)	**S7 after subtraction (S)**	**Ratio O/S**
ADP (kg Sb eq)	2,961.37	1,591.25	1.86
GWP (kg CO_2 eq)	485,281.86	-132,007.38	-3.68
ODP (kg CFC-11 eq)	$6.68 \cdot 10^{-2}$	$-6.78 \cdot 10^{-2}$	-0.98
HTP (kg 1,4-DB eq)	108,570.87	54,313.06	2.00
FETP (kg 1,4-DB eq)	16,067.94	8,118.17	1.98
METP (kg 1,4-DB eq)	60,990,670.70	33,366,770.26	1.83
TETP (kg 1,4-DB eq)	2,224.29	1,729.46	1.29
POFP (kg C_2H_4 eq)	159.03	125.64	1.27
AP (kg SO_2 eq)	3,177.29	-5,771.35	-0.55
EP (kg PO_4^{3-} eq)	1,598.98	-3,523.67	-0.45

In contrast to the case of mussel shell management, Table 5.6 reveals that the assumption of avoided burdens greatly affected the characterization results for mussel organic waste valorization. Thus, the values for ADP, HTP, FETP and METP were reduced by half. Other impact categories (TETP and POFP) also presented lower characterization values although the reduction was less notable. Even several impact categories (GWP, ODP, AP and EP) had characterization values that entail desirable potential environmental impacts.

5.4.3. Implementation into the mussel case study

Finally, the implementation of S6 and S7 (both systems assuming avoided products) into the general mussel case study is discussed.

According to the inventories for S3 in Chapter 4, when 100 tonnes of mussel shell waste are managed, 23 tonnes of canned mussel flesh have been previously produced. Therefore, S6 should not be assessed as an isolated system but together with S3, which also embeds S1 and S7. Figure 5.7 shows the contribution of each of the systems to every impact category. As observed on the whole, the potential impacts strictly due to S6 are generally lower than those linked to systems S1 (mussel culture) and S3 (canned mussel production), even though operations performed in mussel canning factories are highly optimized (Barros et al. 2009b).

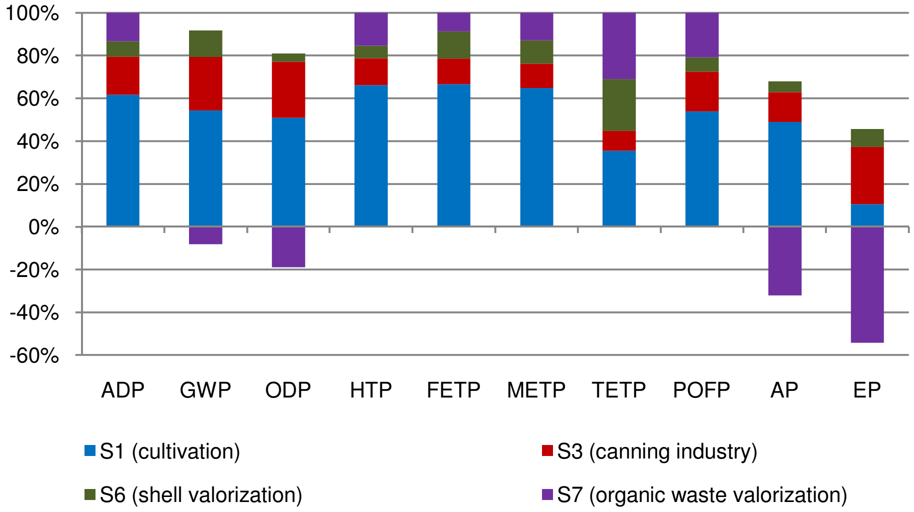

Fig. 5.7. *Contributions to the environmental impact potentials when considering the management of mussel shell waste within the mussel case study*

Similarly, according to the inventories for S2 and S3 in Chapter 4, the management of 100 tonnes of mussel organic waste typically involves a previous production of 137 tonnes of canned mussel flesh and 948 tonnes of purified fresh mussels. In this framework, S7 should be analyzed along with S2 and S3, which embed S1 and S6. Figure 5.8 reflects the contribution of these systems to the different impact categories. The potential impacts linked to S7 are generally lower than those regarding the rest of the systems, especially those associated with fresh mussel purification in dispatch centres (S2) and mussel culture (S1).

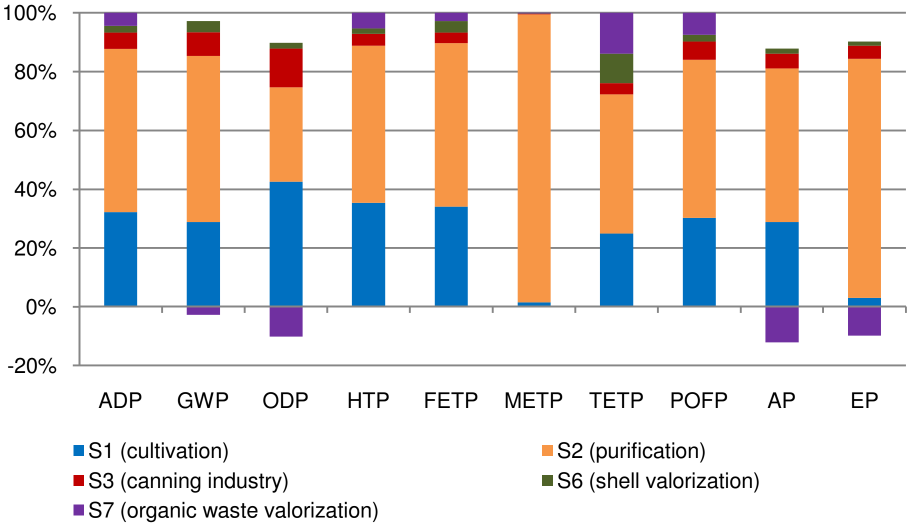

Fig. 5.8. *Contributions to the environmental impact potentials when considering the management of mussel organic waste within the mussel case study*

5.5. Conclusions, recommendations and perspectives

From the environmental characterization for mussel shell valorization, it is recommended to act on the calcination process (minimization of propane consumption, evaluation of alternatives to propane, optimization of gas treatment) as well as on the current waste management practices (sludge valorization, use of processing ashes), along with additional actions regarding haulage and electricity use. Furthermore, the assessment of a set of three hypothetical improvement potentials (use of glycerine instead of propane, use of the processing ashes, and dispatch of sludge to valorization) proved that a future scenario implementing these actions could lead to a worse environmental performance for S6 unless only the ash and sludge measures are taken.

This chapter showed that motivation for mussel shell waste valorization is mainly focused on its performance when compared to other management options, and not merely on the production of calcium carbonate. In this sense, mussel shell waste incineration was proved to be highly discouraged, while disposal to landfill involves some concerns such as land occupation and socioeconomic drawbacks.

The environmental characterization for mussel organic waste valorization led to recommend improvements on the ingredient ratio (minimization of the demand of oil, milk, aromas and spices), the thermal energy demand and the transport of mussel pâté.

Moreover, the relevance of assuming avoided products when characterizing mussel organic waste management was proved. This reduction assumption counteracts the environmental penalty for this waste treatment. This is especially important when including the mussel organic waste treatment in the general case study.

Finally, from the implementation of mussel shell valorization and mussel organic waste valorization into the mussel case study, it is concluded that S6 and S7 contribute to the environmental potential impacts to a lesser extent than systems S1 (mussel culture), S2 (mussel purification) and, generally, S3 (mussel transformation in canning factories).

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SECTION III.

APPLICATION OF LIFE CYCLE ASSESSMENT IN INTENSIVE AQUACULTURE. THE TURBOT SECTOR

Chapter 6

Life Cycle Assessment of feed for aquaculture[1]

Summary

Section III deals with the application of LCA to the Galician turbot sector as representative of the marine intensive aquaculture.

Because of the expected relevance of feed for aquaculture, Chapter 6 starts the environmental assessment of intensive aquaculture by providing the LCA of aquafeed production. This study comprised feed for marine intensive aquaculture, as well as feed for continental aquaculture. As a result, aquafeed formulation was identified as the focus on which improvement actions should be focused.

Marine aquafeed production as presented in this chapter will be implemented as a background process into the case study of Galician turbot aquaculture in Chapter 7.

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[1] Iribarren, D., Moreira, M.T., Feijoo, G. (2010). "Life Cycle Assessment of aquaculture feed and application within the turbot sector". J Clean Prod (in review)

Index

6.1. Introduction

The current situation concerning the exploitation of sea resources has brought about a rapid growth in aquaculture due to its potential to reverse the trend towards depletion (Ahmed 2003). However, aquaculture does not lack a certain degree of controversy, especially with regard to feeding within the intensive aquaculture sector (El Universo 2008). Consequently, a wide range of evaluations are needed in order to assess fishing and aquaculture, including environmental analyses. In this sense, LCA has often been used as a valid environmental management tool to evaluate both fishing (e.g. Ziegler & Valentinsson 2008) and aquaculture (e.g. Mungkung et al. 2006).

The existing LCA studies on intensive aquaculture cover different species; however, despite the diversity of LCAs for the environmental characterization of intensive aquaculture practices, a common conclusion can be drawn: the leading role played by feed, as stated by Grönroos et al. (2006) and Aubin et al. (2009), among others. In fact, feed production is often found as the major contributor to potential environmental impacts in intensive aquaculture (Papatryphon et al. 2004a, 2004b).

Hence, this chapter discusses the LCA of feed production for intensive aquaculture. Aquafeed for both marine and continental aquaculture are object of study in order to identify their environmental hot spots. Furthermore, marine aquafeed production will be implemented into the LCA of Galician turbot aquaculture in the next chapter.

Feed composition for marine aquaculture species differ from that for continental species. Thus, the former usually involves 55% proteins, 12% lipids and 1.6% phosphorus for the farming of fish such as turbot, while the latter generally entails lower contents of proteins (around 45%) and phosphorus (1%) for the aquaculture of fish such as rainbow trout (Aubin et al. 2006).

The sustainable development of intensive aquaculture is highly dependent on the maintenance of water quality and on the suitable use of nutrients by farmed species. As a general rule, there are four key questions in fish feeding: what, how, when and how much. The right combination of the specific answers to these questions for each of the species and each of the different farming conditions results in the maximum use of the growing capacity for each aquaculture farm and, therefore, in a maximum economic yield.

Most of the fish farmed in Spain are either strict carnivores or omnivores. Consequently, diets are usually rich in proteins (40-60%), which gives rise to an important nitrogen excretion. Current trends in fish feeding try to decrease nitrogen loss by increasing nitrogen retention while controlling the ratio of digestible protein to total digestible energy. Given the high market price of protein sources –mainly fish meal–, research in aquafeed factories pursues the maximum protein use as main goal (Sanz 2009).

Furthermore, lipid content is also a primary factor in modern aquaculture diets. Aquafeed manufacturers tend to prepare feed where proteins are to be incorporated into muscles, whereas lipids arise as energy products for metabolic use. In this sense, a high lipid content (16-35%) leads to protein saving and excellent growth. Furthermore, phosphorus supply in fish diets is another key aspect. Phosphorus is generally supplied at percentages around 1% (Sanz 2003).

Aquafeed are currently formulated according to the ratio of digestible protein to digestible energy so greater growth is attained with higher ratios. Nowadays, each of the farmed species has its specific diets in accordance with its particular requirements. Moreover, there is a wide range of specific diets concerning different stages in the production cycle such as larval diets for marine fish, medicated feed, etc.

A percentage around 50% of the production costs of intensive farming is due to feed cost. This fact denotes maturity in the intensive aquaculture sector since feed consumption (variable cost) is directly related to final production and, therefore, to final economic yield (Sanz 2003, 2009).

6.2. Methods

The goal of this chapter consists in the environmental assessment of marine and continental aquafeed. Then, in Chapter 7, this evaluation will be incorporated into a wider case study where the Galician turbot sector is analyzed from an LCA perspective.

6.2.1. System boundaries

Aquafeed production was analyzed from raw material production to product transport. As shown in Figure 6.1, seven subsystems were defined to perform this life cycle study.

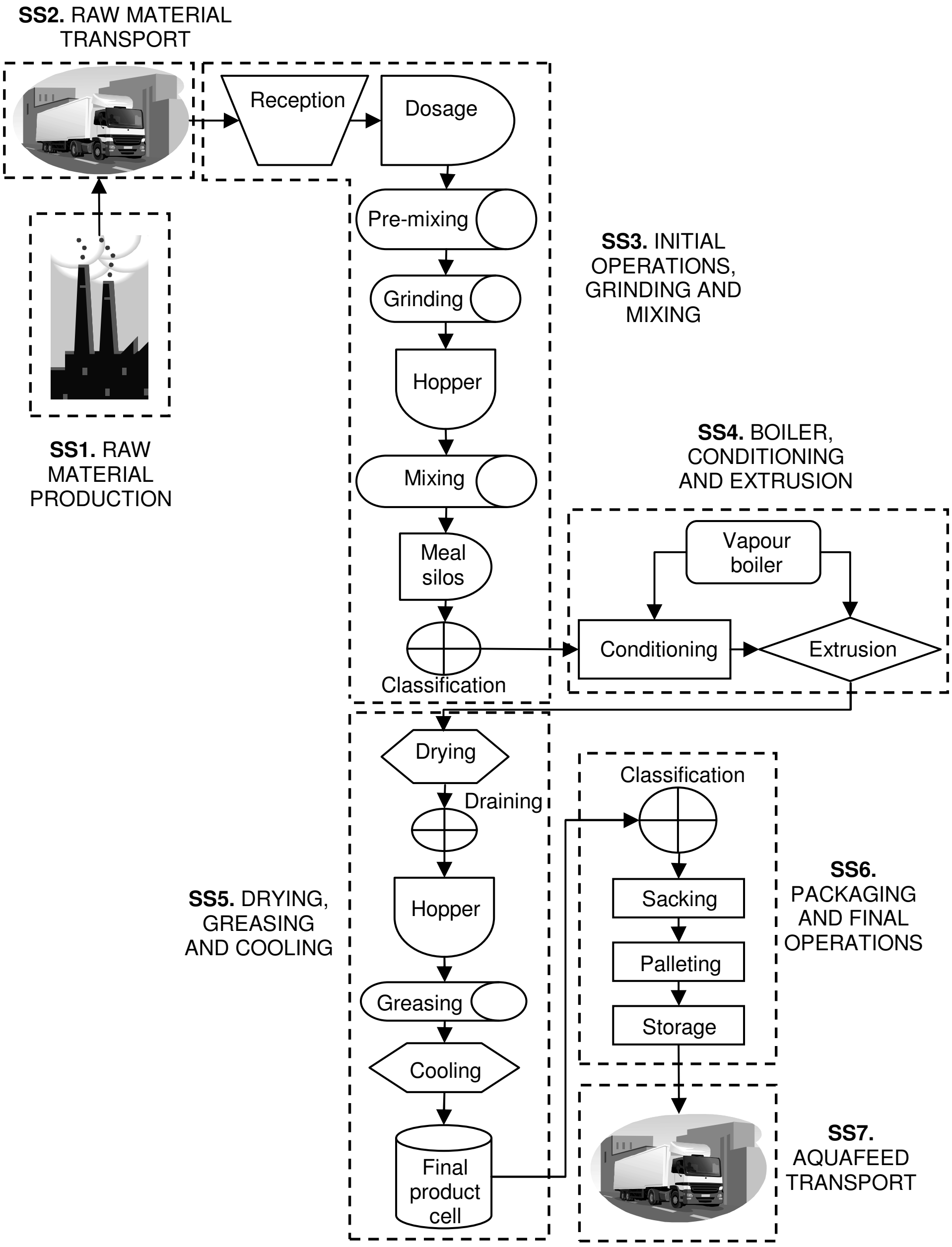

Figure 6.1. *Subsystems for the LCA of aquafeed production*

The process for aquafeed production is simple. All raw materials required for the industrial production of aquafeed –which are previously produced in specific factories (SS1)– are transported by lorry to the aquafeed plant (SS2). Next, SS3 involves the reception, grinding and mixing of the aquafeed ingredients. The resulting mixture is conditioned and extruded (SS4). Afterwards, drying, greasing and cooling are required. These activities constitute subsystem SS5, where the final product is obtained. This product is then packaged and stored (SS6). Finally, aquafeed is transported by lorry towards its final destinations (SS7).

This study deals with both continental and marine feed for aquaculture. The main difference lies in the ingredients required. Therefore, from an LCA perspective, the subsystem primarily affected is SS1, which includes raw material production as a set of background processes.

The production of ingredients and chemicals, the management of waste streams as well as the production and transport of energy carriers were involved as background processes.

6.2.2. Functional unit

The FU for the LCA of marine feed production is 1 tonne of marine aquafeed. Similarly, for the assessment of continental feed, the FU is 1 tonne of continental aquafeed.

6.2.3. Data acquisition and assumptions

Data acquisition

Data for the LCA of feed production for aquaculture came from one of the most important factories in Spain, with an annual production around 50,000 tonnes of aquafeed.

Therefore, primary activity data were used to quantify the direct inputs and outputs linked to the assessed aquafeed facility. On the other hand, background processes for the LCA of aquafeed were taken into consideration via the use of the ecoinvent database as a source of secondary data for transport (Spielmann et al. 2007) as well as for the production of chemicals (Althaus et al. 2007) and energy carriers (Dones et al. 2007), and also for waste treatment (Doka 2007).

Assumptions

The quantification of capital goods was avoided (Renou et al. 2008) on the basis of the long life estimated for the installations (more than 20 years).

The only difference between marine and continental aquafeed was assumed to be the raw materials produced in SS1. The rest of subsystems were considered to entail the same inventory for both feeds. In other words, apart from data for the subsystem regarding raw material production (SS1), which are specific for each type of aquafeed (continental and marine), primary data for the other subsystems were collected without distinguishing feed for continental aquaculture from feed for marine aquaculture. Input-output data from the assessed aquafeed factory referred to the total production of 21 different feed products for both continental species (rainbow trout, salmon, Nile tilapia, common carp and Adriatic sturgeon) and marine species (gilthead bream, European sea bass, turbot, Senegalese sole, meagre, eel and Kuruma prawn). These 21 products were jointly considered as they were just one single aquafeed product.

Finally, electricity production corresponds to the electricity production mix for Spain as presented in the ecoinvent database (Dones et al. 2007). This assumption was thought as the most accurate approach for this case study.

6.2.4. Life cycle inventory

Table 6.1a-d gathers the inventories for marine aquafeed production. As observed, ingredients and energy carriers are the main inputs to the system.

Table 6.1a. *Inventory data for marine aquafeed production: SS1, SS2 and SS3*

INPUTS					
From the technosphere					
1. Electricity (SS3)	19.13	kWh	9. Haemoglobin (SS1)	60.00	kg
2. Water (SS3)	0.05	m^3	10. Animal fat and oil (SS1)	50.00	kg
3. Fish meal (SS1)	192.50	kg	11. Pea protein (SS1)	50.00	kg
4. Soya beans (SS1)	189.95	kg	12. Rape meal (SS1)	43.00	kg
5. Wheat grains (SS1)	144.50	kg	13. Soya oil (SS1)	30.00	kg
6. Recycled fish (SS1)	80.00	kg	14. Calcium carbonate (SS1)	16.00	kg
7. Fish oil (SS1)	78.00	kg	15. Vitamins and minerals (SS1)	6.05	kg
8. Blood meal (SS1)	70.00	kg	16. Raw material transport (SS2)	504.08	t·km
OUTPUTS					
To the technosphere					
1. Product			2. Waste to treatment		
Mixture (SS3)	1.00	t	Effluent to municipal sewer (SS3)	0.05	m^3
			Solid discharge to combustion (SS3)	0.32	kg
			Solid discharge to landfill (SS3)	0.01	kg

Table 6.1b. *Inventory data for marine aquafeed production: SS4*

INPUTS					
From the technosphere					
1. Electricity	89.75	kWh	3. Water	0.58	m^3
2. Natural gas	158.59	kWh	4. Mixture from SS3	1.00	t
OUTPUTS					
To the technosphere			**Emissions to air**		
1. Product			1. CO_2	101.07	kg
Extruded mass	1.40	t	2. CO	5.93	g
2. Waste to treatment			3. SO_2	1.01	g
Effluent to municipal sewer	0.18	m^3	4. NO_x	26.39	g NO_2
Feed discharge to biogas	0.08	kg			
Solid discharge to combustion	0.64	kg			
Solid discharge to landfill	0.03	kg			

Table 6.1c. *Inventory data for marine aquafeed production: SS5*

INPUTS					
From the technosphere					
1. Electricity	57.58	kWh	3. Water	0.07	m^3
2. Natural gas	409.72	kWh	4. Extruded mass from SS4	1.40	t
OUTPUTS					
To the technosphere					
1. Product			2. Waste to treatment		
Unpackaged product	1.00	t	Effluent to municipal sewer	0.07	m^3
			Feed discharge to biogas	0.32	kg
			Solid discharge to combustion	0.32	kg
			Solid discharge to landfill	0.01	kg

Table 6.1d. *Inventory data for marine aquafeed production: SS6 and SS7*

INPUTS					
From the technosphere					
1. Electricity	11.34	kWh	4. Unpackaged product from SS5	1.00	t
2. Polyethylene	3.22	kg	5. Feed transport (SS7)	530.00	t·km
3. Polypropylene	0.76	kg			
OUTPUTS					
To the technosphere					
1. Product			2. Waste to treatment		
Dispatched product	1.00	t	Plastic to recycling	0.46	kg

The corresponding inventories for continental aquafeed are the same, apart from a key aspect: the raw materials produced in SS1. Table 6.2 shows a list of the ingredients which should replace those of Table 6.1a when establishing the life cycle inventory of continental feed.

Table 6.2. *Ingredients for 1 tonne of continental aquafeed (SS1)*

INPUT	kg/t aquafeed	INPUT	kg/t aquafeed
Fish meal	284.20	Soya oil	60.00
Wheat grains	174.50	Animal fat and oil	50.00
Soya beans	156.50	Rape meal	31.50
Fish oil	117.50	Haemoglobin	30.00
Blood meal	100.00	Vitamins and minerals	5.80

6.3. Results

As in the previous section, SimaPro 7 was the software used for the computational implementation of the inventories (Goedkoop et al. 2008), and the ecoinvent database was chosen for background processes.

Classification and characterization following ISO guidelines were performed to assess the potential environmental impact of inputs and outputs from the LCIs. CML was the method used for the environmental characterization of aquafeed production. The ten impact categories considered were AP, ODP, ADP, GWP, EP, POFP, FETP, METP, TETP and HTP.

The environmental characterization of aquafeed production revealed what subsystems accounted for a greater potential impact. Thus, Figure 6.2 shows the percentage contribution of the seven subsystems to the potential environmental impacts associated with the production of marine feed.

As observed in Figure 6.2, SS1 (raw material production) involved contribution percentages ranging from 18% (GWP) to 99% (TETP), and arose as the main contributor to all impact categories except for GWP. This latter had SS4 (boiler, conditioning and extrusion) as top contributor, accounting for a percentage of 36%. The rest of subsystems showed contributions below 17% for the different impact categories. Especially, SS3 (initial operations, grinding and mixing) and SS6 (packaging and final operations) entailed very low percentages, ranging from 0% to only 3%.

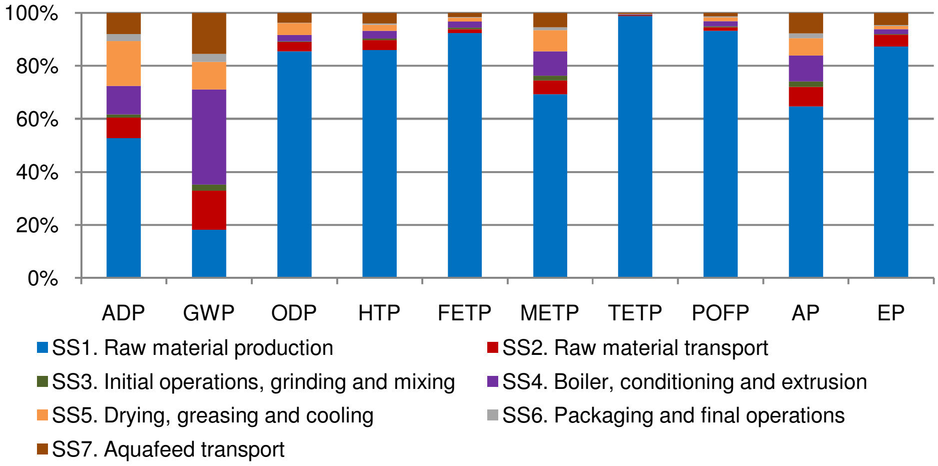

Figure 6.2. *Subsystem contribution to the potential environmental impacts for marine aquafeed production*

Regarding continental aquafeed, the difference in the ingredients gave rise to different characterization results. In this sense, Table 6.3 compares the characterization results linked to SS1 (raw material production) for marine and continental feed. Relevant changes were observed. For instance, GWP for continental feed was more than twice the value for marine feed. On the contrary, EP was much lower for continental aquafeed. These changes in the values for SS1 resulted in notable changes in the final characterization values for the whole system, as gathered in the third column of Table 6.3.

Table 6.3. *Comparison of the characterization results for marine and continental aquafeed*

Impact category	**Ratio SS1 continental/SS1 marine**	**Ratio Total continental/Total marine**
ADP	1.29	1.15
GWP	2.33	1.24
ODP	1.44	1.37
HTP	1.07	1.06
FETP	1.14	1.13
METP	1.32	1.22
TETP	0.74	0.74
POFP	0.85	0.86
AP	1.19	1.12
EP	0.18	0.29

Furthermore, the processes behind potential environmental impacts could be identified. The range of processes involved in aquafeed production is very wide, so a summary of the most relevant ones results more convenient. This process selection is presented in Table 6.4 for the production of marine feed. All sections with a contribution greater than 5% were collected in this table.

Table 6.4. *Process contribution (%) in marine aquafeed production*

Category **Section**	**ADP**	**GWP**	**ODP**	**HTP**	**FETP**	**METP**	**TETP**	**POFP**	**AP**	**EP**
Fish meal (SS1)	25.12	31.05	69.61	18.20	6.05	37.01	0.79	-1.07	13.98	-77.39
Soya beans (SS1)	2.43	9.43	0.89	27.01	1.11	2.54	0.06	88.13	17.82	69.22
Wheat grains (SS1)	6.86	-18.79	2.41	17.22	4.14	11.47	1.20	1.59	12.65	29.15
Fish oil (SS1)	3.01	6.12	7.62	1.83	0.62	3.72	0.06	0.46	3.47	2.07
Blood meal (SS1)	2.43	4.77	0.76	2.31	0.34	2.09	0.16	0.85	5.03	1.35
Pea protein (SS1)	2.34	-0.11	0.99	6.67	6.11	2.37	3.05	0.46	3.55	53.62
Rape meal (SS1)	1.48	-20.10	0.50	3.20	45.33	2.21	91.98	1.32	3.22	6.77
Soya oil (SS1)	2.85	4.33	1.06	4.46	27.67	3.03	1.25	1.93	7.18	25.97
Raw material transport (SS2)	7.65	14.73	3.58	3.83	1.53	5.20	0.34	1.25	7.41	4.41
Atmospheric emissions (SS4)	0.00	23.57	0.00	0.01	0.00	0.00	0.00	0.02	0.31	0.20
Natural gas (SS4)	5.21	1.35	1.54	0.29	0.06	1.15	0.02	0.13	0.18	0.11
Electricity (SS4)	5.50	10.58	0.87	2.46	1.51	7.50	0.22	1.77	9.36	1.31
Natural gas (SS5)	13.45	3.49	3.97	0.75	0.17	2.96	0.04	0.34	0.47	0.27
Electricity (SS5)	3.53	6.79	0.56	1.58	0.97	4.81	0.14	1.13	6.00	0.84
Product transport (SS7)	8.05	15.49	3.76	4.03	1.60	5.46	0.36	1.31	7.79	4.63
TOTAL (%)	89.90	92.69	98.12	93.84	97.20	91.53	99.67	99.61	98.44	122.53

Among this reduced set, the role of those processes involving raw material production stood out, as well as the contribution of transport, electricity use and atmospheric emissions (from SS4) to the global warming category, and the contribution of natural gas use to ADP.

6.4. Discussion and identification of improvement potentials

The application of LCA to aquafeed production resulted in the identification of the corresponding hot spots from an environmental perspective. These hot spots are mainly related to raw material production. In particular, soya beans, fish meal and wheat grains were the most contributing raw materials. This fact is closely linked to the demand of great amounts of these materials according to the current aquafeed formulation.

Moreover, if global warming is of particular interest, additional hot spots would also include transport and the emissions to air from boilers.

Therefore, improvement actions within aquafeed production should be focused on the:

- Environmental analysis of new ingredient ratios. Different combinations of the ingredients are possible. However, suitable contents of proteins, lipids and phosphorus have to be guaranteed. The selection of new ingredient ratios depends on what environmental impact categories are preferred for mitigation. For example, formulations that use more soya beans and wheat grains but less fish meal are expected to entail a better environmental performance regarding ADP, GWP, ODP, FETP and METP.
- Environmental assessment of new raw materials. In addition to changes in ingredient ratios, research on novel protein sources for aquafeed should continue. In this sense, novel raw materials should be assessed from an environmental perspective in order to discuss the potential environmental consequences of replacement. For instance, novel fish meals leading to a better environmental profile for this key raw material would entail relevant environmental improvements in the environmental performance of aquafeed production.
- Revision of the logistical planning with regard to product and raw material transport. This measure is directed towards the minimization of the number of

trips and travel distances required to satisfy the transport needs of raw materials and products in aquafeed factories, so economic and environmental improvements are achieved. GWP, ADP and AP would be the impact categories which would most profit from this measure.

- Minimization of the natural gas demand. This reduction would involve improvements in GWP due to lower levels of emissions to air, as well as in ADP because of the decrease in natural gas amount.

6.5. Conclusions, recommendations and perspectives

This chapter has proved the suitability of LCA to evaluate the environmental performance of aquafeed production. The use of this management tool provided chain transparency and accountability, and led to the identification of the most relevant issues within this case study.

Recommendations for aquafeed manufacturers are centred on raw material production. Thus, different raw materials and/or ingredient ratios should be assessed.

The LCA performed for aquafeed production is useful for its implementation into the study of the environmental performance of intensive aquaculture plants. Specifically, the LCA for marine aquafeed will be used in the next chapter to faithfully assess the Galician turbot sector from an LCA perspective.

6.6. References

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Chapter 7

Life Cycle Assessment of the turbot sector[1]

Summary

In the previous chapter, the LCA of aquafeed production was performed in order to be used within the life cycle study of the turbot aquaculture, guaranteeing that this key background process is suitable for its implementation into the LCA of the Galician turbot sector, which is the core of Chapter 7.

This chapter evaluates the environmental performance of Galician turbot culture and consumption according to LCA methodology. Thus, the environmental hot spots and improvement potentials regarding turbot aquaculture were identified. In particular, electricity use in hatching facilities arose as the main hot spot within turbot aquaculture, ahead of aquafeed and diesel use in ongrowing plants.

Finally, a rough comparison between intensive (turbot) and extensive (mussel) aquaculture was established on the basis of an equitable functional unit. As a result, extensive (mussel) aquaculture generally showed a worse environmental performance.

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[1] Iribarren, D., Moreira, M.T., Feijoo, G. (2010). "Life Cycle Assessment of aquaculture feed and application within the turbot sector". J Clean Prod (in review)

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7.1. Introduction

Spanish turbot (*Scophthalmus maximus*) aquaculture activities are mainly developed in Galicia. In 2007, Galician turbot aquaculture provided more than 5,500 tonnes of this finfish, accounting for an economic turnover close to 50 million euros (Xunta de Galicia 2008). Thus, Galician turbot farming involves around 20% of the Spanish production of finfish from marine aquaculture (Sainz et al. 2008). Worldwide, Galicia is the reference region regarding turbot aquaculture with more than half of the total production and turnover in 2006 (FAO 2009).

Therefore, the Galician turbot sector has a top position in the international turbot market. However, its environmental performance had not yet been evaluated from an LCA perspective. A comprehensive study of this sector enables the estimation of characterization results appropriate for their comparison with those for mussel aquaculture. In this way, a comparison between intensive and extensive aquaculture can be established.

Turbot aquaculture started in Scotland in the 1970s. At the beginning of the 1990s the technological development of juvenile production led to the expansion of turbot farming. Nowadays, Spain, Portugal and France have a well established turbot ongrowing industry. Furthermore, turbot is also cultured in Denmark, Germany, Iceland, Ireland, Italy, Norway and Wales with juveniles being supplied mainly from hatcheries in Spain, France and Denmark (Danancher & García-Vázquez 2007).

At turbot hatcheries, eggs are collected from broodstock, fertilized and incubated. Following absorption of the yolk sac, turbot larvae are fed live feed (rotifers followed by *Artemia*). They are then weaned on to a dry pelleted diet before being transferred to the nursery, which is usually on the same site as the hatchery. The aim of the nursery phase is to grow turbot on to a suitable size for transfer to farms. Turbot hatcheries and some farms keep juveniles in small tanks generally indoors in a closed recirculation system, which allows farmers to control the environment in which the fish live. When turbot juveniles reach a suitable weight, they are transferred to large outdoor tanks where they are ongrown to market size. Unlike other marine fish species, turbot is currently ongrown in onshore tanks in either pump ashore or recirculation systems. There have been some trials on the use of sea cages with limited success (AquaTT 2004).

Turbot takes about two years to grow to a market size of approximately 1 kg from fertilized egg. In the ongrowing stage, turbot is fed on a pelleted diet containing no pigment. During this period regular grading is carried out because of differences in turbot growth rates. Depending on market requirements turbot can be grown to weights ranging from 750 g to 2.5 kg. Fillet composition is diet-dependent. Turbot is a healthy source of proteins and is rich in selenium and omega-3 fatty acids.

The site for turbot farms is chosen according to its suitability for land-based fish farming. Common requirements include the availability of land, water, labour, facilities and a market. Turbot farms are usually located adjacent to shallow bays with large tidal exchange (AquaTT 2004). However, the need to increase the quantities of farmed fish to satisfy market demand, by increasing the number and/or productivity of farms, often conflicts with an increasing human demand for potable water and for marine shorelines for recreation. In this sense, the development of marine fish farming in Western Europe is confronted with many environmental limitations. Accessibility to coastal areas is increasingly limited as tourism and recreational activities develop. In the face of these constraints, land-based fish farms have adapted by moving away from the shore and by using new technologies such as liquid oxygen, mechanical filters and biological filters to limit their water use and nutrient release. In addition, they have improved their feeding management, which has limited releases of non-ingested feed and nutrients at the farm level (Aubin et al. 2006, 2009).

7.2. Methods

The goal of this chapter comprises two main purposes. The first one consists in the environmental assessment of the Galician turbot sector. Second, a rough environmental comparison between intensive and extensive aquaculture is sought by using the characterization results available for turbot and mussel aquaculture practices in Galicia.

7.2.1. System boundaries

For the LCA of the Galician turbot sector (Figure 7.1), two main systems were distinguished. On the one hand, turbot intensive farming (S1), which is usually carried out in three different plants: hatching and nursing facility (from turbot egg to young turbot), growing plant (from young to juvenile), and ongrowing plant (from juvenile to adult). Each of these facilities was considered as a separate subsystem. The final product from SS1.3 (i.e., ongrowing and final operations) is the turbot dispatched to retailers. On the other hand, the second system involved household consumption of turbot.

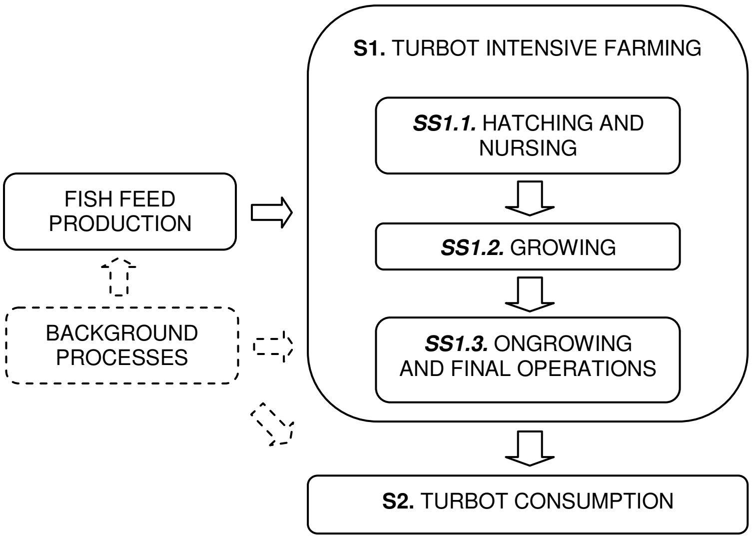

Figure 7.1. *Breakdown of the Galician turbot aquaculture sector for LCA*

Background processes for S1 included not only the previous study concerning aquafeed production (Chapter 6), but also the production of chemicals, waste management, and the production and transport of energy carriers.

Moreover, background processes for S2 involved: production of wrappers; production of ingredients for cooking (oil and salt); production of plastic bags; transport for shopping; electricity production for cooking; and municipal solid waste management.

7.2.2. Functional unit

Turbot sector

The FU for the LCA of the Galician turbot aquaculture sector is 1 kg of turbot for household consumption.

Comparison between aquaculture sectors

The environmental comparison between intensive and extensive aquaculture was established on the basis of a same protein supply: 8.385 g. This value corresponds to the amount supplied by one standard round can of mussels, that is, 43 g of mussel flesh (Isabel 2009).

7.2.3. Data acquisition and assumptions

Data acquisition

Data for turbot farming were based on the information provided by the environmental statements of several Galician plants belonging to worldwide leader companies in the aquaculture sector (Isidro de la Cal 2007; Insuiña-Chapela 2008; Insuiña-Mougás 2008; Insuiña-O Grove 2008; Insuiña-Xove 2008). The total adult turbot production assessed was around 3,500 tonnes.

Therefore, primary activity data were available for the quantification of the direct inputs and outputs associated with turbot farms. Additionally, primary data for turbot consumption concerned the use of electric energy, oil and salt for cooking, the use of wrappers by retailers, and the generation of leftovers as municipal solid waste.

The use of the ecoinvent database to provide secondary data for turbot farming and consumption involved the production of chemicals (Althaus et al. 2007), packaging materials (Hischier 2007) and energy carriers (Dones et al. 2007), as well as transport (Spielmann et al. 2007) and waste treatment (Doka 2007). In addition, for turbot consumption, the quantification of the use of plastic bags and shopping travel was adapted from Hospido et al. (2006).

Assumptions

The quantification of capital goods was avoided (Renou et al. 2008) on the basis of the long life estimated for the installations (more than 20 years).

Electricity production corresponds to the electricity production mix for Spain as presented in the ecoinvent database (Dones et al. 2007).

Finally, waste treatment was included within the system boundaries. However, recycling stayed out because ecoinvent cut-off criteria were followed (Doka 2007).

7.2.4. Life cycle inventory

Table 7.1a-c shows all inputs and outputs for each of the subsystems involved in Galician turbot farming (S1). Feed, chemicals (liquid oxygen) and energy carriers are the main inputs to S1.

Table 7.1a. *Inventory data for turbot aquaculture: SS1.1*

INPUTS					
From the technosphere					
1. Liquid oxygen	2.905	kg	4. Diesel C	0.014	l
2. Feed	0.542	kg	5. Electricity	14.843	kWh
3. Fresh water	0.388	l	6. Turbot eggs	285,714.286	units
From the environment					
1. Seawater	0.360	l			
OUTPUTS					
To the technosphere			**Emissions to the ocean**		
1. Products			1. Suspended solids	1.260	mg
Young turbot (main product)	21.429	g	2. Nitrite	0.047	mg
Turbot eggs	285,714.286	units	3. Phosphate	0.036	mg
2. Waste to valorization			4. TOC	0.468	mg
Paper and cardboard	0.144	g	**Emissions to air**		
Wood	0.505	g	1. SO_2	0.075	g
Plastic	0.173	g	2. CO	0.015	g
PP filters	0.135	g	3. CO_2	0.114	kg
3. Non-hazardous waste without valorization			4. NO_x	0.101	g
Municipal solid waste	0.267	g	5. O_2	0.051	kg
Sludge from septic tank	0.850	g			
Sludge from wash	0.850	g			
Dead fish	0.214	g			
4. Hazardous waste to manager					
Used mineral oil	0.134	g			
Water-hydrocarbons mixture	0.280	g			
Contaminated plastics	0.023	g			
Oil filters	0.009	g			
Metal containers	0.007	g			
Laboratory waste	0.007	g			
Batteries	0.016	g			

Table 7.1b. *Inventory data for turbot aquaculture: SS1.2*

INPUTS					
From the technosphere			**From the environment**		
1. Liquid oxygen	0.299	kg	1. Seawater	1.759	l
2. Feed	0.118	kg			
3. Fresh water	1.897	l			
4. Diesel C	0.068	l			
5. Electricity	3.152	kWh			
6. Young turbot	21.429	g			
OUTPUTS					
To the technosphere			**Emissions to the ocean**		
1. Product			1. Suspended solids	6.685	mg
Juvenile	0.105	kg	2. Nitrite	0.070	mg
2. Waste to valorization			3. Phosphate	0.176	mg
Paper	0.127	g	4. TOC	2.815	mg
Cardboard	0.123	g	**Emissions to air**		
Wood	3.513	g	1. SO_2	0.367	g
Scrap	2.345	g	2. CO	0.072	g
Plastic	1.153	g	3. CO_2	0.557	kg
3. Non-hazardous waste without valorization			4. NO_x	0.495	g
Non-medicated feed plastic bags	0.625	g	5. O_2	0.251	kg
Dead fish	5.722	g			
Organic waste	0.045	g			
Sea organic waste	0.630	g			
4. Hazardous waste to manager					
Fluorescent lights	0.034	g			
Batteries	0.019	g			
Medicated feed	0.561	g			
Contaminated plastics	0.326	g			
Obsolete electronic systems	0.229	g			
Out of order batteries	0.022	g			

Table 7.1c. *Inventory data for turbot aquaculture: SS1.3*

INPUTS					
From the technosphere			**From the environment**		
1. Liquid oxygen	0.274	kg	1. Seawater	15.041	l
2. Feed	0.891	kg			
3. Fresh water	18.115	l			
4. Electricity	2.045	kWh			
5. Diesel B	0.283	l			
6. Diesel C	0.651	l			
7. Juvenile	0.105	kg			
8. Product transport to retailers	0.425	t·km			
OUTPUTS					
To the technosphere			**Emissions to the ocean**		
1. Product			1. Suspended solids	45.395	mg
Dispatched adult turbot	1.000	kg	2. Nitrite	1.526	mg
2. Waste to valorization			3. Phosphate	3.688	mg
Scrap	1.370	g	4. TOC	24.905	mg
Paper and cardboard	1.330	g	**Emissions to air**		
Plastic	15.420	g	1. SO_2	3.507	g
Others (PVC, wood…)	27.447	g	2. CO	0.683	g
3. Non-hazardous waste without valorization			3. CO_2	5.315	kg
Municipal solid waste	13.126	g	4. NO_x	4.729	g
Dead fish	13.504	g	5. O_2	2.397	kg
Organic waste	10.230	g			
4. Hazardous waste to manager					
Spray cans	0.001	g			
Contaminated containers	0.739	g			
Office waste	0.003	g			
Absorbent agents	0.359	g			
Water-hydrocarbons mixture	0.131	g			
Sanitary waste	0.018	ml			
Laboratory waste	0.059	g			

Complementarily, Table 7.2 presents the inventory for household consumption of farmed turbot (S2).

Table 7.2. *Inventory data for turbot consumption*

INPUTS FROM THE TECHNOSPHERE					
1. Materials			2. Transport		
Dispatched adult turbot	1.00	kg	Shopping travel	0.14	m
Paper film	19.88	g	3. Energy		
Plastic film (LDPE)	3.01	g	Electricity	0.16	kWh
Oil	53.86	g			
Salt	7.96	g			
Plastic bags (LDPE)	3.80	g			
OUTPUTS TO THE TECHNOSPHERE: waste to treatment					
1. Municipal solid waste: plastic bags				3.80	g
2. Municipal solid waste: leftovers and others				332.60	g

7.3. Results

As in the previous chapter, SimaPro 7 was the software used for the computational implementation of the inventories (Goedkoop et al. 2008), and the ecoinvent database was chosen for background processes.

Classification and characterization following ISO guidelines were performed to evaluate the potential environmental impact of inputs and outputs from the LCIs. CML was the method used to characterize the environmental performance of the Galician turbot sector. The impact categories assessed were those of the previous chapters: ADP, GWP, ODP, POFP, AP, EP, HTP, FETP, METP and TETP.

In the previous chapter, the environmental performance of aquafeed production was characterized. The LCA for marine aquafeed was here implemented as a reliable background process into the case study of the LCA of turbot aquaculture and consumption.

The environmental characterization of Galician turbot aquaculture (farming and consumption) led to the identification of the most contributing subsystems and processes within this sector.

Figure 7.2 shows what subsystems were found to be the main sources of potential environmental impact.

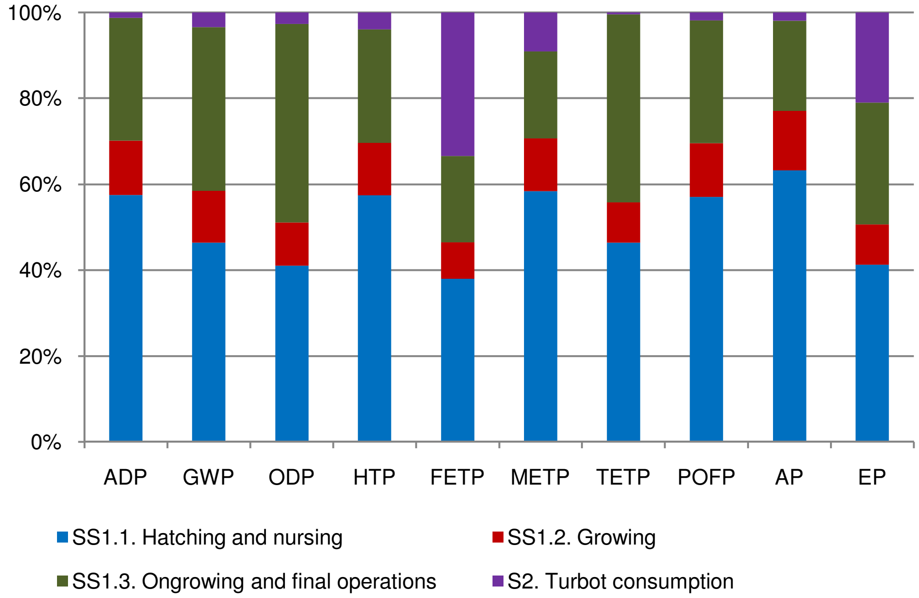

Figure 7.2. *Contribution to the potential environmental impact in turbot aquaculture and consumption*

As observed in Figure 7.2, the role of turbot consumption appeared not to be very contributing except for FETP (percentage contribution of 33%), EP (21%) and, to a lesser extent, METP (9%). On the contrary, hatching and nursing (SS1.1) prevailed for all impact categories except for ODP, where SS1.3 (ongrowing and final operations) arose as the main contributor. The contribution percentages for SS1.1 ranged from 38% (FETP) to 63% (AP), and, for SS1.3, from 20% (FETP) to 46% (ODP). On the other hand, the environmental impact contribution of growing (SS1.2) was deemed relevant but accounting for percentages clearly lower than those of SS1.1 and SS1.3. In fact, the greatest contribution of SS1.2 was linked to AP, with a percentage of 14%.

The following step is to find out what processes were behind the most relevant contributions to the potential environmental impacts. With this aim, Table 7.3 presents the sections which accounted for any impact contribution greater than 5%.

Table 7.3. *Process contribution (%) in turbot culture and consumption*

Category Section	ADP	GWP	ODP	HTP	FETP	METP	TETP	POFP	AP	EP
Liquid oxygen (SS1.1)	7.46	6.07	3.44	7.24	4.71	8.31	6.66	3.77	4.45	2.50
Aquafeed (SS1.1)	2.80	1.19	10.22	5.89	5.93	2.09	23.53	8.32	1.99	7.64
Electricity (SS1.1)	47.05	38.50	27.02	44.19	27.26	47.85	16.10	44.86	56.68	30.56
Aquafeed (SS1.2)	0.61	0.26	2.22	1.28	1.29	0.45	5.12	1.81	0.43	1.66
Electricity (SS1.2)	9.99	8.18	5.74	9.38	5.79	10.16	3.42	9.53	12.04	6.49
Emissions (SS1.3)	0.00	27.27	0.00	0.19	0.00	0.00	0.00	3.19	5.16	5.18
Aquafeed (SS1.3)	4.61	1.96	16.80	9.68	9.75	3.44	38.69	13.67	3.26	12.57
Diesel (SS1.3)	15.98	2.04	23.89	8.81	1.66	8.02	1.83	4.64	3.76	3.93
Electricity (SS1.3)	6.48	5.30	3.72	6.09	3.76	6.59	2.22	6.18	7.81	4.21
Oil (S2)	0.40	0.94	2.20	0.09	0.05	0.06	-0.12	1.19	1.07	18.71
Leftovers management as MSW (S2)	0.05	2.10	0.06	2.90	32.54	8.24	0.19	0.07	0.08	1.66
TOTAL (%)	95.42	93.82	95.32	95.74	92.74	95.20	97.63	97.22	96.74	95.12

As deduced from Table 7.3, the high electricity demand for hatching and nursing was the main reason for the high contribution of SS1.1 to all impact categories.

Aquafeed requirement was also an outstanding contributor, especially for SS1.1 and SS1.3 because of the higher feed demand in these subsystems. This latter result justifies the need to have previously performed a thorough study concerning feed production for aquaculture in Chapter 6.

It should be remarked that emissions to air from SS1.3 involved a contribution of 27% to the global warming category. Additionally, diesel use in SS1.3 entailed contributions of 24% and 16% to ODP and ADP, respectively.

Furthermore, Table 7.3 also reveals that the relevant contribution of turbot consumption to FETP and METP was due to the management of leftovers (along with other waste streams) as municipal solid waste. Finally, the contribution of turbot consumption to EP was associated with the use of oil to cook turbot in households.

7.4. Discussion and identification of improvement potentials

7.4.1. Turbot aquaculture

The main hot spot for turbot aquaculture was found to be electricity use in hatching and nursing facilities, ahead of aquafeed and diesel use for ongrowing.

Hence, improvement actions in mussel aquaculture should pursue the minimization of the electricity demand for hatching.

Additionally, aquaculture plants should promote the production of more environmentally friendly aquafeed. In this sense, aquafeed manufacturers should research on actions focused on those issues previously identified in Chapter 6.

Furthermore, secondary measures should act on the diesel demand within ongrowing facilities.

Actions on turbot consumption would entail positive effects on the environmental performance of the turbot sector, but they are not deemed feasible since the management of leftovers as municipal solid waste is considered unavoidable.

The results and recommendations from the LCA of the Galician turbot aquaculture sector should be useful to encourage farmers to undertake the assessment of the environmental performance of other key farmed fish from intensive aquaculture in Spain such as rainbow trout, gilthead bream and sea bass. Characterization results for these species would differ from those for the turbot case study since each species entails specific intensive farming practices with particular input demands (e.g. differences in aquafeed demand) and, therefore, different output features. However, similarly to turbot farming, relevant environmental roles are expected to be played by energy and feed use for the intensive farming of these species. Actually, as a general rule in intensive aquaculture, these two factors –energy and aquafeed– could be considered the two top contributors to potential environmental impact.

7.4.2. Comparison of aquaculture sectors

As regards aquaculture in Spain, Galicia is the reference region (Xunta de Galicia 2008). The two star products from Galician aquaculture are mussels (*Mytilus galloprovincialis*) and turbot (*Scophthalmus maximus*). These two species involve two different aquaculture modes. On the one hand, mussels are cultured in rafts by means of extensive aquaculture practices. On the other hand, turbot is farmed according to marine intensive aquaculture practices.

In Section II of this dissertation, the Galician mussel sector was assessed from an LCA perspective from farming through processing to consumption as fresh, canned and frozen mussels.

In this chapter, a rough comparison between intensive and extensive aquaculture sectors was performed by adopting turbot and mussels as their respective representatives. This comparison was established on the basis of an equitable functional unit: the same protein supply, 8.385 g of proteins. This value corresponds to the amount of proteins supplied by the consumption of one common round can of mussels (Isabel 2009).

According to available data on protein supply (Consello Regulador 2009; Isabel 2009; Paquito 2009), life cycle inventory data and the conventional market distribution of cultured mussels in Spain (Chapter 4), 8.385 g of proteins are commonly supplied by the joint consumption of 211.75 g of fresh mussels (shell and water included in this weight), 20.39 g of canned mussels (only flesh) and 10.19 g of frozen mussels (only flesh). Alternatively, 52.24 g of farmed turbot are needed to supply the same amount of proteins (Serpeska 2009).

The comparative LCA of the turbot and mussel sectors led to the characterization values gathered in Table 7.4.

Unexpectedly, from the ratios in Table 7.4, a worse environmental performance was associated with extensive (mussel) aquaculture, except for terrestrial and fresh water aquatic ecotoxicity potentials. This result is closely linked to the unsustainable electricity use in mollusc dispatch centres and to the inclusion of capital goods in the inventory of mussel culture, whereas intensive (turbot) aquaculture facilities operate at a more efficient scale and their capital goods were excluded from the analysis.

Table 7.4. *Environmental comparison between intensive and extensive aquaculture sectors on the basis of an equal supply of proteins (8.385 g)*

Impact category	Unit	Turbot sector (intensive aquaculture)	Mussel sector (extensive aquaculture)	Ratio intensive/extensive
ADP	kg Sb eq	$6.13 \cdot 10^{-3}$	$8.08 \cdot 10^{-3}$	0.76
GWP	kg CO_2 eq	1.02	1.03	0.99
ODP	kg CFC-11 eq	$7.92 \cdot 10^{-8}$	$1.17 \cdot 10^{-7}$	0.68
HTP	kg 1,4-DB eq	$1.63 \cdot 10^{-1}$	$2.37 \cdot 10^{-1}$	0.69
FETP	kg 1,4-DB eq	$9.06 \cdot 10^{-2}$	$7.87 \cdot 10^{-2}$	1.15
METP	kg 1,4-DB eq	137.59	3,920.38	0.04
TETP	kg 1,4-DB eq	$5.01 \cdot 10^{-3}$	$2.83 \cdot 10^{-3}$	1.77
POFP	kg C_2H_4 eq	$3.06 \cdot 10^{-4}$	$3.77 \cdot 10^{-4}$	0.81
AP	kg SO_2 eq	$6.66 \cdot 10^{-3}$	$8.31 \cdot 10^{-3}$	0.80
EP	kg PO_4^{3-} eq	$6.24 \cdot 10^{-4}$	$6.49 \cdot 10^{-3}$	0.10

7.5. Conclusions, recommendations and perspectives

LCA proved to be a useful tool to assess the environmental performance of the Galician turbot aquaculture sector. Chain transparency and accountability were among the benefits from the use of LCA in this case study. Moreover, the environmental hot spots within turbot plants were identified.

The main recommendation for turbot farmers consists in the minimization of the electricity demand in hatching facilities. Furthermore, improvements in aquafeed production would also entail relevant benefits regarding the environmental performance of turbot aquaculture plants. In this sense, marine aquafeed was considered as a key environmental issue within turbot aquaculture. This fact stresses the relevance of having used a reliable life cycle inventory for marine aquafeed production.

Finally, a rough comparison between intensive and extensive aquaculture sectors was established by assuming turbot and mussels as their respective representatives. Extensive aquaculture involved a worse environmental profile mainly due to electricity use in mussel dispatch centres and the role played by capital goods for mussel culture.

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SECTION IV.

INSIGHTS IN THE APPLICATION OF LIFE CYCLE ASSESSMENT

Chapter 8

The link between operational efficiency and environmental impacts[1,2]

Summary

Section IV gives insights on the potentials behind the use of Carbon Footprinting (CF) and the combined use of LCA and Data Envelopment Analysis (LCA+DEA).

Environmental impacts depend on the efficiency with which operations are carried out. Where life cycle inventory data are available for multiple similar entities, their respective operational performances can be benchmarked by means of DEA. In chapters 8 and 9, the synergistic use of LCA+DEA is proposed as a methodological approach to link operational efficiency and environmental impacts. In particular, Chapter 8 presents a five-step LCA+DEA method to attain operational benchmarking and eco-efficiency verification while assessing the environmental performance of mussel cultivation sites (rafts). Operational inefficiencies were detected and target performance values were defined for the inefficient sites. This method demonstrated the dependence of environmental impacts on the operational performance, and favoured quantification of potential eco-efficiency gains. This direct link can help to convince managers and operators of the cultivation sites of the double dividend of reducing input consumption to achieve operational efficiency: lower costs and lower environmental impacts.

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Index

8.1. Introduction

8.1.1. The problem of multiple inventory data in LCA

Data availability and quality are critical problems in LCA studies (Weidema & Wesnaes 1996; Reap et al. 2008a). LCA practitioners often have to gather inventory data for a high number of similar facilities in order to ensure sample representativeness for a particular case study. Therefore, it is not unusual to handle multiple input/output data. The way multiple data sets are managed may strongly influence the utility of the assessment. A common solution is to establish an average inventory which includes the average values for the different inputs and outputs. However, the high degree of variability often associated with multiple data sets is a barrier. An alternative approach to dealing with multiple inventories is to carry out individual LCAs for each of the inventories. This approach may better represent variability, but the multiple results may be difficult to interpret.

In such situations, a promising alternative which simultaneously (i) avoids standard deviations, (ii) facilitates the interpretation of the results, and (iii) provides useful additional information is to complement LCA with a non-parametric tool called Data Envelopment Analysis (DEA).

8.1.2. An introduction to DEA

DEA is an established and well-known methodology for non-parametrically estimating the relative efficiency of a number of homogeneous units, commonly designated as Decision Making Units (DMU) (Cooper et al. 2007a; Zhu 2002). Non-parametric estimation means that it does not rely on assumptions that the data come from any specific production function. However, data on the inputs and outputs of the DMUs have to be known. From the observed data and making a minimum of assumptions, DEA determines a Production Possibility Set (PPS) which contains those operating points that are deemed feasible. Then, DEA formulates and solves, for each DMU, an optimization model (usually a Linear Program, LP) producing an efficiency score and a target operating point. The target operating point lies on the efficient frontier and is computed in such a way that it generally uses the same or less inputs to produce identical or more output. In fact, the efficiency score is a measure of the relative improvements in inputs and outputs between the DMU and its assigned target.

Therefore, DEA estimates production efficient frontiers for a number of homogenous units (DMUs); in mathematical terms, these efficient frontiers are said to envelop all units. The region determined by the efficient frontiers is the PPS, and the DMUs on the frontiers constitute the Reference Set. The result for each DMU is an efficiency score and, for those DMU identified as inefficient, a target operating point.

Among many other application fields, DEA has been proposed for the environmental performance analysis of industrial plants, economic sectors, countries, etc. (e.g. Tyteca 1996, 1997; Zaim & Taskin 2000; Dyckhoff & Allen 2001; Korhonen & Luptacik 2004; Sarkis & Talluri 2004; Zhou et al. 2006, 2007; Munksgaard et al. 2007; Kortelainen 2008; Lozano & Gutiérrez 2008). It has also been used for the eco-efficiency assessment of processes and products (Kuosmanen & Kortelainen 2005, 2007a; Barba-Gutiérrez et al. 2009). An interesting recent development is the use of DEA within an Environmental Cost Benefit Analysis (ECBA) approach that takes into account the time dimension of the environmental impacts. Thus, Kuosmanen & Kortelainen (2007b) and Kuosmanen et al. (2009) proposed to discount the flows of environmental impacts and to compute, using an original DEA model, the competitive advantage of a project or policy, competitive advantage that can be used as a surrogate of its life cycle eco-efficiency.

In this chapter, a direct link between operational efficiency and environmental impacts is established with the aid of both DEA and LCA. Assuming that life cycle inventory (LCI) data are available on multiple DMUs, DEA can be used to gauge their efficiency and establish efficiency targets. In this sense, the comparison between the results of the original life cycle impact assessment (LCIA) and those of the LCIA of the computed targets is expected to lead to reduced environmental impacts for the computed targets since, for the same output amount, they will use a lower amount of inputs. Therefore, the proposed approach uses a production DEA model instead of considering environmental impacts as inputs in the DEA model. The latter approach (used for example in Kuosmanen & Kortelainen 2005, 2007; Kortelainen 2008; Barba-Gutiérrez et al. 2009) has the advantage that a smaller number of inputs is usually needed, therefore improving the discriminatory power of DEA in the case of small data samples. Nevertheless, working with life cycle inventory data, directly related to the operation of the facilities, has the advantage of detecting and removing the technical inefficiencies that are the source of unnecessary environmental impact.

8.2. Proposal of an LCA+DEA approach

The goal of this chapter is to propose a regular methodology to perform a joint analysis of operational efficiency and environmental impacts for multiple similar installations using the combined application of LCA and DEA.

8.2.1. The five-step LCA+DEA method

As summarized in Figure 8.1, the proposed LCA+DEA methodology comprises five main steps:

i) LCI for each of the DMUs. In this stage, input and output data for the assessed system are collected.

ii) LCIA for every DMU from the LCI developed in the first step. This second stage constitutes the environmental characterization of the current DMUs' performance.

iii) DEA from the LCIs of the first step: Determination of the operational efficiency of each DMU and calculation of the target DMUs. The use of DEA on the most relevant input/output data leads to computing the relative efficiency of each DMU and setting appropriate efficiency targets. The DEA targets represent virtual DMUs which consume less input and/or produce more output. These targets are calculated by projecting each DMU on the efficient frontier determined by the reference set. Each DMU has its own reference set, so this step should not be misunderstood as a simple calculation of a distance-to-target for the less efficient DMUs through a simple scan of the inventory data sets. Therefore, at this point, the performance of multiple DMUs is benchmarked from an economic/operational perspective.

iv) Environmental characterization of the target DMUs. In this fourth stage, the potential environmental impacts are determined for the virtual DMUs by performing an LCIA with the new LCI data arising from the previous step.

v) Comparison of the potential environmental impacts for the virtual DMUs versus those for the current DMUs. This step shows how environmental impacts depend on the efficiency with which operations are carried out. Links between operational efficiency and environmental impacts are then established and the environmental consequences of operational inefficiencies can be estimated.

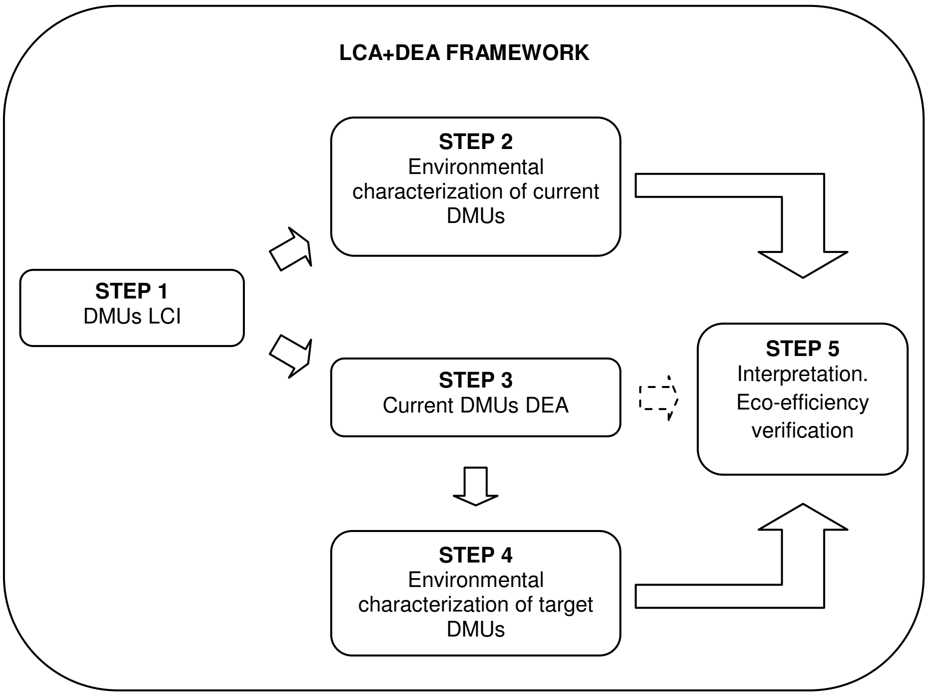


Figure 8.1. *Schematic representation of the five-step LCA+DEA method*

An alternative approach would consist of only three stages. The first two steps would be the same as those described above. However, the third stage would comprise a DEA with a higher number of inputs given the consideration of the potential environmental impacts determined in the second step as inputs for the DEA along with the selected LCI inputs. In this sense, the benchmarking results would directly estimate targets for both LCI inputs/outputs and the potential environmental impacts. This alternative is further developed in Chapter 9.

8.2.2. Before performing DEA

A first question before performing DEA is what number of DMUs is necessary in order to guarantee an adequate assessment since LCA+DEA method demands that LCI data be available for multiple similar installations. From a DEA perspective, each installation represents a DMU. The rule of thumb to determine the minimum sample size in DEA is: $n \geq \max \{m \cdot s, 3 \cdot (m+s)\}$ (Cooper et al. 2007a), where m is the number of inputs used in the DEA study and s is the number of outputs involved.

A second question is what model should be used to perform DEA. In this respect, a wide range of models to perform DEA are available (Zhu 2002). Three factors have to be taken into account when selecting a model:

- Metric. Two options are distinguished concerning metric. Radial metrics try to uniformly reduce all inputs by a certain amount without entailing any decrease in outputs. On the other hand, non-radial metrics compute the percentage improvement along each input and output dimension and average them.
- Orientation. A model can be oriented towards inputs, towards outputs or it can show a mixed orientation. In input-oriented models, the aim is to minimize input amounts, but always achieving at least the same initial amounts for outputs. On the contrary, output-oriented models aim to maximize output amounts without requiring an increase in input values. Finally, mixed (non-oriented) models try both to reduce inputs and to increase outputs.
- PPS display. Even though DEA does not rely on assumptions that the data come from any specific production function, some assumptions are usually made to perform DEA. The three common assumptions are (i) convexity, (ii) scalability and (iii) free disposability of inputs and outputs. Convexity means that any linear combination with non-negative coefficients of the two input-output vectors corresponding to two real DMUs defines a feasible operating point related to a virtual DMU. Scalability consists of the feasibility to generate a virtual operating point by multiplying all the inputs and outputs of the input-output vector of a DMU by a certain scalar. Finally, free disposability of inputs and outputs means that, given a feasible input-output vector, other operating points that consume more and/or produce less are also feasible. When the three assumptions are made, the PPS is said to display Constant Returns to Scale (CRS). On the other hand, if convexity and free disposability but not scalability are assumed, then the PPS displays Variable Returns to Scale (VRS).

It is important to highlight that DEA models are already implemented in software tools such as DEA-Solver-Pro (Saitech 2009), an Excel-based program designed on the basis of Cooper et al. (2007a).

8.2.3. Potentials of the LCA+DEA method

LCA presents a number of methodological challenges. Some of them are related to LCA itself, such as the current lack of accepted methodologies to assess the social and economic dimensions of product or service systems. On the other hand, other challenges affect particular areas of study where currently under-represented environmental impact categories constitute a barrier to LCA application. For example, in the case of fisheries, these challenges arise in accounting for fishery-specific impacts such as benthic disturbance due to bottom trawling or the biodiversity impacts caused by discards and by-catch (Pelletier et al. 2007). The LCA+DEA method may contribute to partly resolving these challenges; for instance, by providing an economic perspective or benchmarking discard levels.

LCA is traditionally focused only on environmental impacts. In fact, ISO documentation limits LCA's purview to environmental effects (ISO 2006a, 2006b). From a sustainable development perspective, this may limit the capability of LCA to support decisions (Reap et al. 2008b). In this sense, the LCA+DEA methodology adds an economic dimension to the assessment by evaluating the operational performance of the DMUs. Therefore, complementary use of DEA provides LCA with a stronger potential to support decision making because it facilitates benchmarking both the environmental and the operational performance of the assessed DMUs.

Eco-efficiency is based on creating more goods and services while using fewer resources and creating less waste and pollution. The term eco-efficiency was coined by the World Business Council for Sustainable Development (WBCSD) to demand the delivery of competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity throughout the entire life cycle to a level at least in line with the Earth's estimated carrying capacity (Schmidheiny 1992). The joint application of DEA and LCA allows the benchmarking of the environmental and operational performance of DMUs, which provides a basis for targeting effective means of reducing environmental impacts if the determined operational targets are achieved. The proposed five-step LCA+DEA method is in accordance with the eco-efficiency concept and arises as a simple approach geared towards sustainability and not limited to environmental impacts.

Application of DEA models gives rise to other advantages related to the specific model chosen by the user. For instance, weighted models enable users to assign weights to inputs and outputs corresponding to the relative importance of items; for example, instead of giving the same priority to every input reduction, the reductions in each of the inputs can be differently weighted by giving more priority to the reduction of those inputs that contribute more to the environmental impact categories (Thanassoulis & Dyson 1992).

DEA models can also be used to address certain issue areas for which accepted impact assessment methods have not been developed. For example, for the LCA of fisheries, DEA OBad models, which minimize "bad outputs" from product or service systems, might be used to account for discards. DEA usually assumes that producing more outputs relative to less input resources is a criterion of efficiency. However, this clearly does not apply to undesirable outputs, such as polluting emissions or wasted resources. In the presence of undesirable outputs, technologies with better (desirable) outputs and less bad (undesirable) outputs relative to less input resources should be recognized as efficient (Cooper et al. 2007a). In the case of fisheries, the LCA+DEA method can employ an OBad model to integrate discarding in the assessment by benchmarking its values on the basis of real discard LCI data (i.e., minimizing discard values from a DEA perspective), rather than by implementing a new impact category from an LCA perspective.

8.3. Application to mussel cultivation sites

The five-step LCA+DEA method is here illustrated with a case study based on the LCA for mussel culture. In Chapter 3, although input and output data were available for a number of different mussel cultivation sites (rafts), LCA was performed on a virtual average installation. On the contrary, in this chapter, individual LCAs are performed for a sample of 62 rafts. In addition, from the LCI results of the current sites, a benchmarking analysis of the sample is carried out with the aim of identifying operational inefficiencies that allow for reduction of input consumption and increase of production. For those DMUs where such inefficiencies were found, an LCIA of their computed target was performed and the obtained results were compared with those of the current DMU. In this way, a quantification of the effects on the different environmental impact categories of reducing excess input consumption can be obtained.

8.3.1. Introduction to DEA for mussel cultivation sites

The third step of the proposed LCA+DEA method is the DEA of the current DMUs. In the mussel case study, the objective is to benchmark the production processes of the different DMUs using as inputs their LCI data and as output their corresponding FU. This is carried out by means of DEA, which is schematically shown in Figure 8.2.

The proposed DEA model only has inputs and outputs. The direct emissions from the DMU (e.g. wastewater from vessels for mussel farming) have been modelled as inputs. Alternatively, these direct emissions from the DMU can be modelled as undesirable outputs but that would lead to more complex DEA models that assume weak disposability of the undesirable outputs.

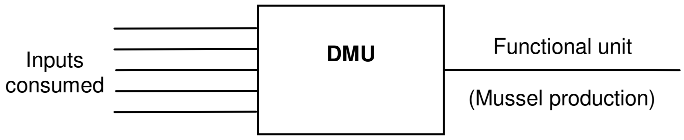


Figure 8.2. *Schematic representation of the operational efficiency analysis*

The first task is to determine the PPS. Although DEA is a non-parametric approach, some assumptions are usually made. As previously stated, when convexity, scalability and free disposability are assumed, the PPS is said to display Constant Returns to Scale (CRS); while if the convexity and free disposability assumptions are made but not that of scalability, then the PPS is said to display Variable Returns to Scale (VRS).

The criterion for assuming CRS or VRS is not clear-cut. Generally, if the DMUs function in a competitive market then it can be assumed that they operate at their Most Productive Scale Size (Banker 1984) and therefore CRS may prevail. On the contrary, whenever there are reasons to suspect that not all the DMUs operate at an optimal scale, it may be safer to assume VRS.

In the mussel culture case study, if CRS are assumed it is not necessary that the FU be the same for the different DMUs. Otherwise, if VRS are assumed, the

LCI data of the different DMUs need to correspond with a common FU identically defined for all of them.

DEA captures the dependence between the inputs and the outputs, inferring from the observed data the maximum amounts of outputs that can be obtained from different combinations of the inputs. It is important to emphasize that one of the advantages of DEA is its non-parametric character, so DEA does not make any assumption about the functional form of the dependence between outputs and inputs. In other words, DEA does not need or use any specific knowledge about the process. DEA makes only some basic assumptions (like convexity, scalability and free disposability), and with those few assumptions and the observed data it is able to extrapolate a PPS that contains the feasible operating points.

DEA works by projecting each DMU in turn onto the efficient frontier. This is done formulating, for each DMU, an optimization model that computes the maximum improvement that can be achieved on the inputs and outputs of the observed DMU. Improvements mean lower values for the inputs and higher values for the outputs. Since the optimization model used in DEA restricts the search to those operating points with less input and more output than the DMU being projected, it is guaranteed that the projection dominates the observed DMU. A DMU is efficient if it is not possible to find another operating point that dominates it; while, if the optimization model computes an operating point that consumes less input and/or produces more output, then the DMU is inefficient.

There are different ways of measuring the overall improvement depending on the metric and the orientation used. In the mussel farming case study, a mixed orientation and a non-radial metric are used.

In order to formulate the proposed DEA model, some notation needs to be introduced:

- N → number of DMUs
- j = 1, 2,…, N → index on the DMUs
- M → number of different inputs consumed by the DMUs
- k = 1, 2,…, M → index on inputs consumed
- x_{kj} → amount of input k consumed by DMU j
- y_j → FU used in the LCI of DMU j

- 0 → index of DMU being projected
- $(\lambda_{10}, \lambda_{20}, ..., \lambda_{N0})$ → vector of coefficients of linear combination for assessing unit 0
- θ_{k0} → reduction factor in the consumption of input k by DMU 0
- γ_0 → output increase factor for DMU 0
- ϕ_0 → efficiency score for DMU 0

ERM-CRS model

$$\phi_0 = \text{Min} \quad \frac{\frac{1}{M}\sum_{k=1}^{M}\theta_{k0}}{\gamma_0} \qquad \text{(Model 8.1)}$$

subject to

$$\sum_{j=1}^{N}\lambda_{j0}\cdot x_{kj} \leq \theta_{k0}\cdot x_{k0} \quad \forall k$$

$$\sum_{j=1}^{N}\lambda_{j0}\cdot y_j \geq \gamma_0\cdot y_0$$

$$0 \leq \theta_{k0} \leq 1 \quad \forall k$$

$$\gamma_0 \geq 1$$

$$\lambda_{j0} \geq 0 \ \forall j$$

The above DEA model corresponds to the Enhanced Russell graph Measure (ERM), whose aim is to minimize the ratio of average input reduction to average output increase. Since ERM is, in principle, a more complex approach than the conventional Debreu-Farrell (DF) efficiency measure (Charnes et al. 1978) and, in addition, its dual does not have a meaningful economic interpretation, the selection of this efficiency measure must be justified. An important drawback of the DF efficiency measure is that it neglects remaining inputs and output slacks and therefore does not account for all sources of inefficiency. ERM does not involve this problem. Furthermore, ERM has a number of desirable properties, such as units invariance, strong monotonicity of inputs and outputs, etc. Thus, it is easy to see that $0 \leq \phi_0 \leq 1$. Moreover, $\phi_0 = 1$ if and only if DMU 0 is efficient, i.e. it is not possible for DMU 0 either to reduce its inputs without reducing its output or to increase its output without increasing its inputs. In addition, ϕ_0 is units-invariant, i.e. it does not change if the units of measurement of the output or of a certain input is changed. Finally, although this optimization model is in principle non-linear, it can be transformed into a simple LP (Pastor et al. 1999; Cooper et al. 2007b).

Therefore, the ERM efficiency score is a single figure that represents the ratio of the average inputs reduction to the output increase. The inputs reductions and the output increase are measured in relative terms, i.e. multiplying the actual, observed input or output value by a factor less than or greater than one, respectively. The average reduction is less than (or equal to) one and the average output increase is greater than (or equal to) one, so the ERM efficiency scores is less than (or equal to) one. Equality only occurs when no input can be reduced and the output cannot be increased. In that case, it is not possible for the observed DMU to improve its efficiency level.

The solution of Model 8.1 sets a target for each DMU 0. The target refers to the inputs and output of an efficient virtual operating point that generally consumes less input and produces more output than currently does DMU 0. Such targets are easily computed with the following expressions:

$$\hat{x}_{k0} = \sum_{j=1}^{N} \lambda_{j0} \cdot x_{kj} \leq \theta_{k0} \cdot x_{k0} \leq x_{k0} \quad \forall k \qquad \text{(Equation 8.1)}$$

$$\hat{y}_0 = \sum_{j=1}^{N} \lambda_{j0} \cdot y_j \geq \gamma_0 \cdot y_0 \geq y_0 \qquad \text{(Equation 8.2)}$$

The virtual targets defined by these two equations are environmentally characterized in the fourth step of the LCA+DEA method, a task which is performed by using the CML method with the new LCI data. For the target corresponding to each DMU 0 the same FU which was used for DMU 0 (i.e., y_0) should be used. This means that, if $\gamma_0 > 1$, then the input targets should have to be scaled down by this factor, i.e. $(\hat{x}_{k0}/\gamma_0, y_0)$ are the inputs and output, respectively, of the virtual DMU whose environmental impacts are to be computed in the fourth step.

ERM-VRS model

Before proceeding to the application of the approach for mussel rafts, it should be commented that in the VRS case, since the FU of all the units is the same ($y_j = y \quad \forall j$), the DEA model to be used would be:

$$\phi_0 = \text{Min} \quad \frac{\frac{1}{M}\sum_{k=1}^{M}\theta_{k0}}{\gamma_0} \qquad \text{(Model 8.2)}$$

subject to

$$\sum_{j=1}^{N}\lambda_{j0}\cdot x_{kj} \le \theta_{k0}\cdot x_{k0} \quad \forall k$$

$$\sum_{j=1}^{N}\lambda_{j0}\cdot y \ge \gamma_0 \cdot y$$

$$\sum_{j=1}^{N}\lambda_{j0} = 1$$

$$0 \le \theta_{k0} \le 1 \quad \forall k$$

$$\gamma_0 \ge 1$$

$$\lambda_{j0} \ge 0 \quad \forall j$$

From the constraints, it is easy to prove that $\gamma_0 = 1$ must hold for every feasible solution to Model 8.2. Therefore, the model simplifies to:

$$\phi_0 = \text{Min} \quad \frac{1}{M}\sum_{k=1}^{M}\theta_{k0} \qquad \text{(Model 8.3)}$$

subject to

$$\sum_{j=1}^{N} \lambda_{j0} \cdot x_{kj} \leq \theta_{k0} \cdot x_{k0} \quad \forall k$$

$$\sum_{j=1}^{N} \lambda_{j0} = 1$$

$$0 \leq \theta_{k0} \leq 1 \quad \forall k$$

$$\lambda_{j0} \geq 0 \quad \forall j$$

Consequently, the virtual DMU for which the LCIA is performed in the fourth step of the method is $(\hat{x}_{k0}, y_0)$, with $\hat{x}_{k0}$ computed as in Equation 8.1.

8.3.2. Application of the five-step LCA+DEA approach

The proposed approach is here applied to a sample of 62 mussel cultivation sites (rafts) from Chapter 3. Since LCI data for the 62 sites are available together with the corresponding annual production quantities (step 1), the goal is to evaluate each individual site from two perspectives: operational efficiency and environmental impact. Next, both analyses are linked according to the five-step LCA+DEA method. Hence, unlike in Chapter 3, the use of a generic (average) mussel cultivation site was avoided.

Table 8.1 presents the selection of the inputs and the output which are subject of DEA. The corresponding LCI data for the 62 DMUs are shown in Table 8.2.

Table 8.1. *Labels and units of measurement for the selected inputs and output*

Label	Inputs	Units	Label	Inputs	Units
I-1	Diesel B	l/year	I-9	Nylon	kg/year
I-2	Lubricating oil	l/year	I-10	Cotton	kg/year
I-3	Paint	l/year	I-11	Tar oil	l/year
I-4	Wastewater from vessel	l/year	I-12	Wood for raft	kg/year
I-5	Wood for auxiliary boat	kg/year	I-13	HDPE for plastic pegs	kg/year
I-6	Iron for floats	kg/year	I-14	Electricity for capital goods	GJ/year
I-7	Iron for shackle chain	kg/year	**Label**	**Output**	**Units**
I-8	Concrete for anchoring block	kg/year	O	Production of mussels of commercial size	t/year

Table 8.2. *Input and output data for the 62 DMUs*

DMU	O	I-1	I-2	I-3	I-4	I-5	I-6	I-7	I-8	I-9	I-10	I-11	I-12	I-13	I-14
1	67.3	600.0	15.0	22.5	69.4	306.2	838.7	83.0	800.0	221.7	23.0	109.6	2,414.3	26.9	181.7
2	112.2	1,000.0	25.0	37.5	115.6	510.3	838.7	83.0	800.0	369.5	38.3	109.6	2,414.3	26.9	302.9
3	74.5	750.0	10.4	10.4	38.5	170.1	1,718.2	172.9	1,575.8	245.4	25.5	150.0	5,160.5	26.9	201.1
4	82.6	825.0	11.5	11.5	42.4	187.1	1,718.2	172.9	1,575.8	272.0	28.2	150.0	5,160.5	26.9	222.9
5	96.9	975.0	13.5	13.5	50.1	221.1	1,718.2	172.9	1,575.8	319.3	33.1	150.0	5,160.5	26.9	261.7
6	105.0	1,050.0	14.6	14.6	54.0	238.1	1,718.2	172.9	1,575.8	345.9	35.9	150.0	5,160.5	26.9	283.5
7	115.0	1,680.6	10.7	7.6	56.5	249.5	1,397.9	138.3	1,260.7	272.0	28.2	80.0	4,345.7	26.9	310.5
8	125.0	1,833.3	11.7	8.3	61.7	272.1	1,397.9	138.3	1,260.7	295.6	30.7	80.0	4,345.7	26.9	337.5
9	135.0	1,986.1	12.6	9.0	66.8	294.8	1,397.9	138.3	1,260.7	319.3	33.1	80.0	4,345.7	26.9	364.5
10	68.4	571.4	3.9	4.1	15.1	50.0	1,397.9	138.3	1,166.7	168.5	17.5	200.0	4,345.7	26.9	184.7
11	85.2	714.3	4.8	5.1	18.9	62.5	1,397.9	138.3	1,166.7	209.9	21.8	200.0	4,345.7	26.9	230.0
12	103.2	857.1	5.8	6.1	22.7	75.0	1,397.9	138.3	1,166.7	254.2	26.4	200.0	4,345.7	26.9	278.6
13	120.0	1,000.0	6.8	7.1	26.4	87.5	1,397.9	138.3	1,166.7	295.6	30.7	200.0	4,345.7	26.9	324.0
14	136.8	1,142.9	7.8	8.2	30.2	100.0	1,397.9	138.3	1,166.7	337.0	35.0	200.0	4,345.7	26.9	369.4
15	154.8	1,285.7	8.7	9.2	34.0	112.5	1,397.9	138.3	1,166.7	381.4	39.6	200.0	4,345.7	26.9	418.0
16	171.6	1,428.6	9.7	10.2	37.8	125.0	1,397.9	138.3	1,166.7	422.8	43.8	200.0	4,345.7	26.9	463.3
17	77.4	1,140.6	22.8	5.7	34.2	206.3	1,164.9	115.3	972.2	228.3	23.3	200.0	3,621.4	22.4	208.8
18	82.5	1,218.8	24.4	6.1	36.6	220.4	1,164.9	115.3	972.2	243.3	24.8	200.0	3,621.4	22.4	222.6
19	88.4	1,296.9	25.9	6.5	38.9	234.5	1,164.9	115.3	972.2	307.5	31.9	200.0	3,621.4	26.9	238.7
20	91.8	1,343.8	26.9	6.7	40.3	243.0	1,164.9	115.3	972.2	319.3	33.1	200.0	3,621.4	26.9	247.9
21	60.3	1,333.3	16.7	2.5	30.8	102.7	1,612.9	159.6	1,923.1	198.1	20.5	50.0	5,014.2	26.9	162.8
22	64.8	1,444.4	18.1	2.7	33.4	111.3	1,612.9	159.6	1,923.1	212.9	22.1	50.0	5,014.2	26.9	175.0
23	115.2	2,555.6	31.9	4.8	59.1	196.9	1,612.9	159.6	1,923.1	378.4	39.2	50.0	5,014.2	26.9	311.0
24	119.7	2,666.7	33.3	5.0	61.7	205.5	1,612.9	159.6	1,923.1	393.2	40.8	200.0	5,014.2	26.9	323.2
25	80.0	2,000.0	20.0	20.0	60.0	246.6	838.7	83.0	600.0	173.8	17.4	200.0	2,607.4	19.0	216.0
26	90.0	2,250.0	22.5	22.5	67.5	277.4	838.7	83.0	600.0	195.6	19.5	200.0	2,607.4	19.0	243.0
27	107.0	2,666.7	26.7	26.7	80.0	328.8	838.7	83.0	600.0	316.3	32.8	200.0	2,607.4	26.9	288.9
28	123.0	3,083.3	30.8	30.8	92.5	380.1	838.7	83.0	600.0	363.6	37.7	200.0	2,607.4	26.9	332.1
29	72.9	1,895.8	21.7	21.7	89.4	191.4	1,497.7	148.2	1,071.4	185.1	18.6	100.0	4,656.1	20.2	196.8
30	93.6	2,420.8	27.7	27.7	114.1	244.5	1,497.7	148.2	1,071.4	272.5	27.9	100.0	4,656.1	23.5	252.7
31	103.5	2,683.3	30.7	30.7	126.5	271.0	1,497.7	148.2	1,071.4	340.0	35.3	100.0	4,656.1	26.9	279.5
32	90.0	2,000.0	50.0	50.0	60.0	328.8	698.9	103.8	1,500.0	250.9	25.6	200.0	3,054.0	22.4	243.0
33	66.4	1,250.0	12.5	8.3	77.1	340.2	1,075.3	106.4	897.4	245.4	25.5	20.0	3,342.8	26.9	179.3
34	93.6	1,750.0	17.5	11.7	107.9	476.3	1,075.3	106.4	897.4	345.9	35.9	20.0	3,342.8	26.9	252.7
35	40.0	1,200.0	20.0	4.0	18.5	98.0	559.1	83.0	1,600.0	236.5	24.5	12.5	1,000.0	26.9	108.0
36	42.0	1,260.0	21.0	4.2	19.4	102.9	559.1	83.0	1,600.0	248.3	25.8	12.5	1,000.0	26.9	113.4
37	45.0	1,350.0	22.5	4.5	20.8	110.2	559.1	83.0	1,600.0	266.1	27.6	12.5	1,000.0	26.9	121.5
38	50.0	1,500.0	25.0	5.0	23.1	122.5	559.1	83.0	1,600.0	295.6	30.7	12.5	1,000.0	26.9	135.0
39	52.0	1,560.0	26.0	5.2	24.1	127.4	559.1	83.0	1,600.0	307.5	31.9	12.5	1,000.0	26.9	140.4
40	55.0	1,650.0	27.5	5.5	25.4	134.7	559.1	83.0	1,600.0	325.2	33.7	12.5	1,000.0	26.9	148.5
41	57.0	1,710.0	28.5	5.7	26.4	139.6	559.1	83.0	1,600.0	337.0	35.0	12.5	1,000.0	26.9	153.9
42	59.0	1,770.0	29.5	5.9	27.3	144.5	559.1	83.0	1,600.0	348.8	36.2	12.5	1,000.0	26.9	159.3
43	60.1	466.7	29.1	20.0	61.7	272.1	1,374.6	138.3	1,260.7	198.1	20.5	109.6	4,023.8	26.9	162.3
44	119.4	933.3	58.2	40.0	123.3	544.3	1,374.6	138.3	1,260.7	393.2	40.8	109.6	4,023.8	26.9	322.2

Table 8.2. *Input and output data for the 62 DMUs (cont.)*

DMU	O	I-1	I-2	I-3	I-4	I-5	I-6	I-7	I-8	I-9	I-10	I-11	I-12	I-13	I-14
45	64.0	800.0	48.0	32.0	24.0	163.3	1,048.4	103.8	650.0	236.5	24.5	100.0	3,319.6	26.9	172.8
46	80.0	1,000.0	60.0	40.0	30.0	204.1	1,048.4	103.8	650.0	295.6	30.7	100.0	3,319.6	26.9	216.0
47	96.0	1,200.0	72.0	48.0	36.0	244.9	1,048.4	103.8	650.0	354.8	36.8	100.0	3,319.6	26.9	259.2
48	83.0	2,177.1	41.7	41.7	77.1	340.2	1,397.9	138.3	1,260.7	245.4	25.5	109.6	4,345.7	26.9	224.1
49	117.0	3,047.9	58.3	58.3	107.9	476.3	1,397.9	138.3	1,260.7	345.9	35.9	109.6	4,345.7	26.9	315.9
50	50.0	250.0	3.5	10.0	18.5	76.8	1,048.4	103.8	850.0	141.9	14.7	50.0	3,259.3	26.9	135.0
51	80.0	400.0	5.6	16.0	29.6	122.9	1,048.4	103.8	850.0	174.4	18.1	50.0	3,259.3	26.9	216.0
52	125.0	500.0	7.0	20.0	37.0	153.7	1,233.4	122.1	1,000.0	351.8	36.5	50.0	3,834.4	26.9	337.5
53	137.5	600.0	8.4	24.0	44.4	184.4	1,233.4	122.1	1,000.0	384.3	39.9	50.0	3,834.4	26.9	371.3
54	140.0	750.0	10.5	30.0	55.5	230.5	1,397.9	138.3	1,133.3	393.2	40.8	50.0	4,345.7	26.9	378.0
55	80.0	598.3	17.1	8.5	15.8	96.3	838.7	83.0	600.0	307.5	31.9	100.0	2,400.0	26.9	216.0
56	120.0	897.4	25.6	12.8	23.7	144.5	838.7	83.0	600.0	369.5	38.3	100.0	2,400.0	26.9	324.0
57	100.0	1,196.6	34.2	17.1	31.6	192.7	838.7	83.0	720.0	384.3	39.9	100.0	2,800.0	26.9	270.0
58	160.0	1,914.5	54.7	27.4	50.6	308.3	838.7	83.0	720.0	473.0	49.1	100.0	2,800.0	26.9	432.0
59	50.0	2,393.2	68.4	34.2	63.2	385.4	1,352.8	133.9	774.2	192.2	19.9	200.0	3,871.0	26.9	135.0
60	50.0	833.3	8.3	4.2	30.0	102.1	815.4	69.2	630.3	198.1	20.5	109.6	1,666.7	26.9	135.0
61	100.0	1,666.7	16.7	8.3	60.0	204.1	815.4	69.2	630.3	263.1	27.3	109.6	1,666.7	26.9	270.0
62	100.0	2,500.0	25.0	12.5	90.0	306.2	815.4	69.2	500.0	393.2	40.8	109.6	1,666.7	26.9	270.0
Total	5,685	88,825	1,485	1,020	3,145	13,400	70,616	7,226	70,143	18,161	1,880	6,966	210,109	1,628	15,351

Note that, in the case of mussel aquaculture, emissions to air are directly proportional to the amount of diesel B consumed for powering the ship (input I-1). Therefore, it is not necessary to consider it explicitly since by minimizing input I-1, at the same time, the direct emissions from the DMU are being minimized. Similarly, the wastewater emissions to the ocean have been modelled as input I-4.

With regard to the carrying out of the LCAs to environmentally characterize mussel culture in the 62 studied rafts (step 2), it is worth summarizing some key aspects already involved in Chapter 3. First, remember that the system under study included the different stages considered for mussel culture, from seed collection to the packaging prior to fresh mussel delivery towards processing factories. Construction, operation and maintenance of rafts and auxiliary boats were also included. On the other hand, data acquisition was based on questionnaires filled out by a significant number of skippers of auxiliary boats in the most representative area for mussel farming in Galicia (Ria de Arousa). Therefore, data used for these LCAs basically consisted of real *in situ* data for mussel farming in Galician rafts; additionally, for background processes, ecoinvent database was used (Frischknecht et al. 2007). Finally, for the execution of the life cycle impact assessments, SimaPro 7 was the specific software used for the computational implementation of the life cycle inventories (Goedkoop et al. 2008), and the environmental impact assessment method was CML, taking into account the ten conventional impact categories used throughout this dissertation: ADP, GWP, ODP, HTP, FETP, METP, TETP, POFP, AP and EP.

Table 8.3. *ERM-CRS efficiency scores and eco-efficiency ratios*

DMU	ϕ_0 **(%)**	**Eco-efficiency ratio (%)**	**DMU**	ϕ_0 **(%)**	**Eco-efficiency ratio (%)**
1	56.62	98.83	32	57.29	98.33
2	75.95	99.60	33	79.96	96.77
3	52.11	97.11	34	*100.00*	97.72
4	60.77	97.20	35	79.91	99.73
5	*100.00*	97.52	36	82.38	98.98
6	59.25	97.67	37	85.89	98.34
7	*100.00*	98.41	38	91.28	97.63
8	*100.00*	98.61	39	93.32	97.47
9	*100.00*	98.79	40	96.25	97.26
10	74.10	98.62	41	98.15	97.13
11	78.19	98.64	42	*100.00*	97.20
12	*100.00*	98.99	43	47.48	98.07
13	93.42	99.22	44	63.09	98.76
14	91.18	99.53	45	52.41	97.41
15	*100.00*	99.81	46	58.25	97.73
16	*100.00*	*100.00*	47	64.00	98.20
17	58.38	97.77	48	49.25	95.77
18	59.83	97.85	49	59.13	97.14
19	59.04	97.77	50	68.93	*100.00*
20	60.03	97.88	51	*100.00*	*100.00*
21	*100.00*	94.64	52	*100.00*	*100.00*
22	80.79	94.77	53	*100.00*	*100.00*
23	*100.00*	96.90	54	*100.00*	99.64
24	*100.00*	97.06	55	*100.00*	*100.00*
25	*100.00*	97.78	56	*100.00*	*100.00*
26	*100.00*	98.17	57	73.45	99.00
27	71.15	98.50	58	*100.00*	*100.00*
28	*100.00*	98.85	59	34.31	91.49
29	51.47	95.26	60	55.17	*100.00*
30	55.43	96.09	61	*100.00*	99.25
31	56.44	96.43	62	*100.00*	98.28

Table 8.3 shows the efficiency scores computed with Model 8.1 (step 3). As marked in italics, 24 of the 62 DMUs resulted efficient. The average efficiency was 59.69%. For comparison purposes, Table 8.3 also shows the eco-efficiency ratios computed using environmental impacts directly as inputs (and production as single output). As observed, the range of values for the eco-efficiency ratio is smaller than for ERM-CRS and the number of efficient DMUs is much lower (just nine). Since both efficiency scores differ, the operational efficiency analysis carried out in this chapter is not equivalent to the eco-efficiency ratio analysis. As a result, the two efficiency scores are only weakly correlated. Thus, their corresponding Pearson correlation coefficient is 0.415 (significant at 1% level) and the Spearman rank order correlation coefficient is 0.313 (significant at 5% level).

Unlike common coastal, offshore and deep-sea fleets, auxiliary vessels for mussel rafts do not compete with each other for a limited resource (wild fish). Instead, these vessels transport variable amounts of farmed mussels between two fixed positions: the mussel raft served and the port where the mussels are landed. Therefore, the efficiency of this fleet is strongly dependent on three key factors: (i) the distance the vessels cover from the mussel rafts until landing, (ii) the number of mussel rafts assigned to each vessel, and (iii) the mussel production of each raft. In this sense, auxiliary vessels that cover increased distances should try to assist a higher number of rafts (Vázquez-Rowe et al. 2010).

For the inefficient DMUs, their associated virtual targets were computed with DEA. On the other hand, the target for each efficient DMU coincides with its actual operating point. Once defined the virtual targets, their corresponding potential environmental impacts were estimated by implementing into SimaPro 7 the new LCIs based on the virtual targets computed with DEA (step 4).

Figures 8.3 and 8.4 show the potential environmental impacts per tonne of output for the original DMUs versus those for their associated virtual targets (step 5). As expected, the environmental impacts of the virtual targets were almost always lower than those of the original DMUs. However, as observed just a few times in the case of the global warming category (GWP), it may happen that the virtual target has a higher impact. This occurs when the consumption of a certain input (in this case inputs I-5 and I-12) positively affects to an environmental impact category (it reduces the potential impact), which is related to the environmental impact assessment method used. In fact, inputs I-5 and I-12 involve the use of hardwood logs at forest including only the splitting of residual wood with a diesel powered splitting machine; additionally, according to the available inventories for wood (Werner et al. 2007), land use of forest as well as natural drying in the forest are considered, but air emissions released from the wood are not accounted for because the same emissions would occur if the wood would not be used. Thus, since DEA seeks to reduce the inputs, indirectly, it may increase that environmental impact.

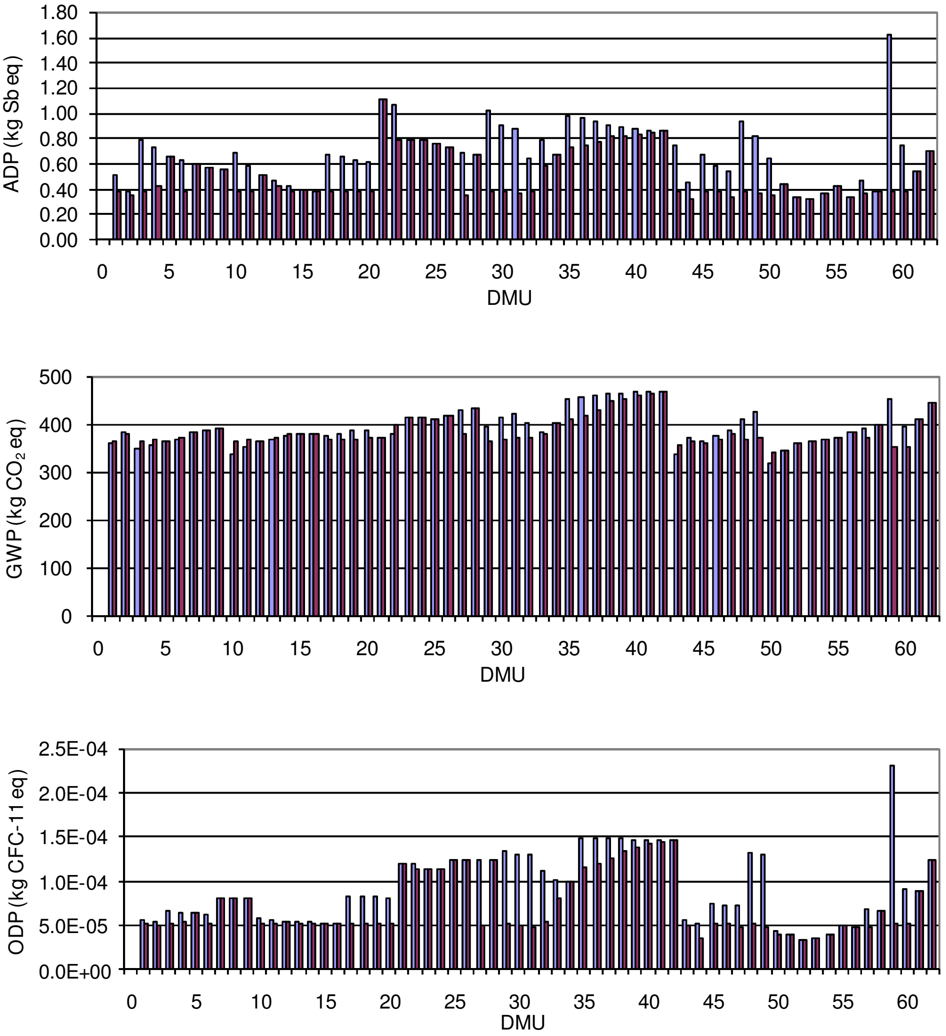
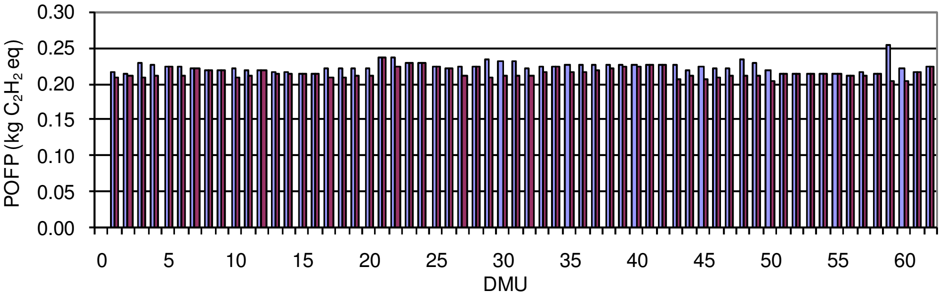
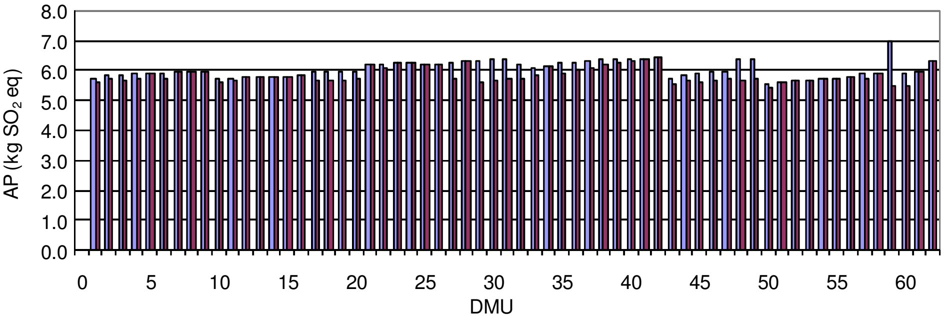


Figure 8.3. *Conventional impact potentials per tonne of output for the original DMUs (blue bars) and the virtual targets (purple bars)*





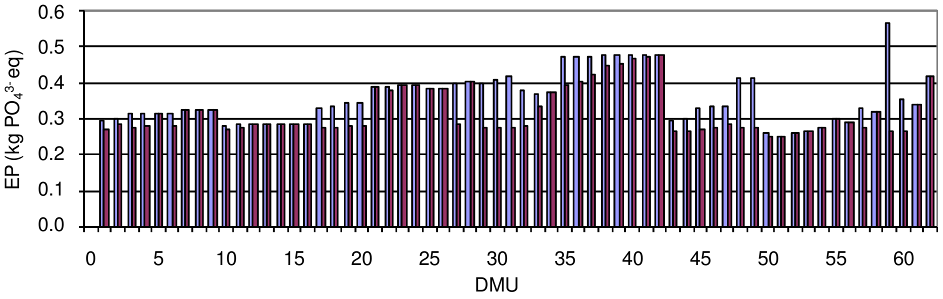


Figure 8.3. *Conventional impact potentials per tonne of output for the original DMUs (blue bars) and the virtual targets (purple bars) (cont.)*

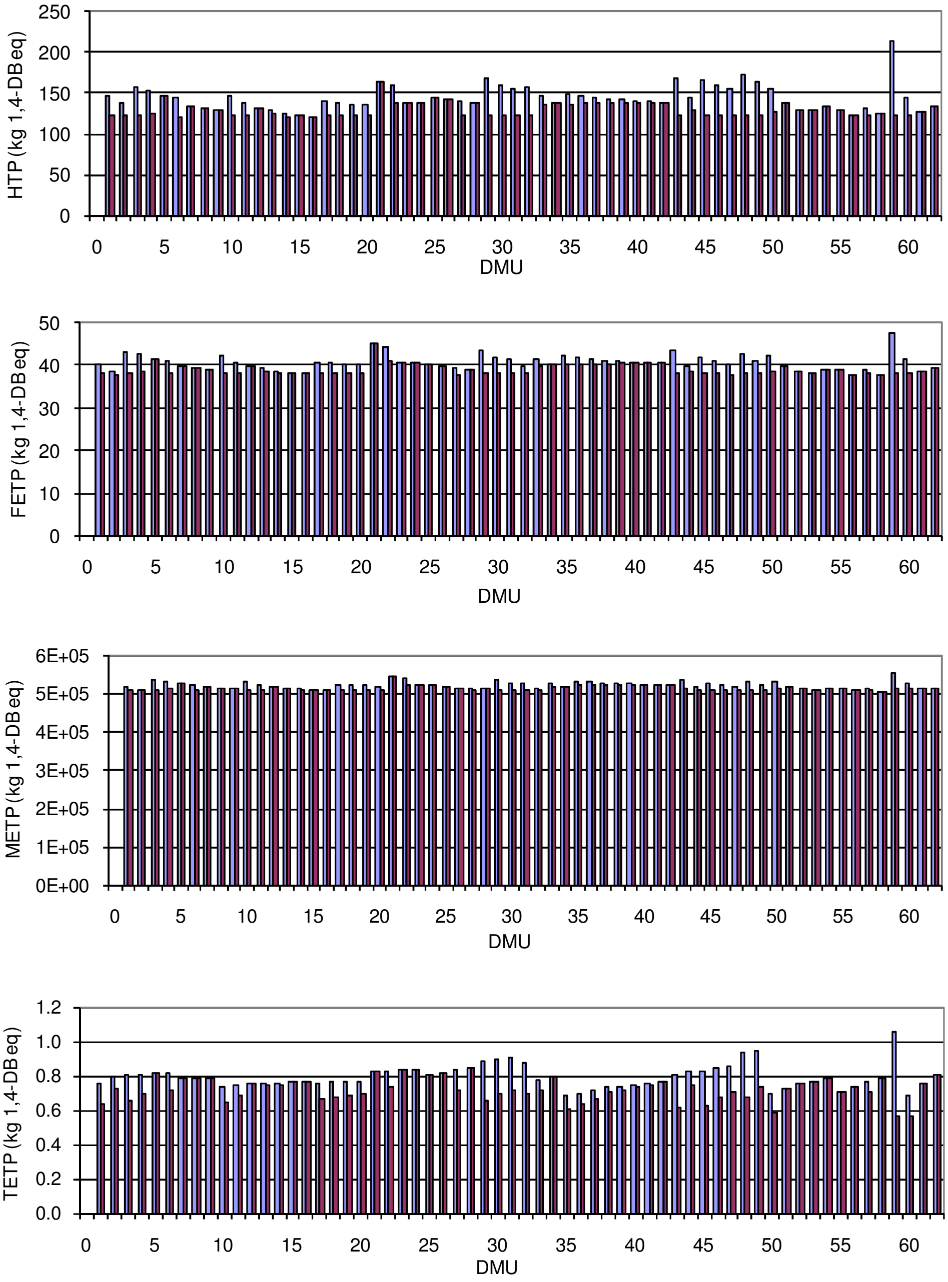


Figure 8.4. *Toxicity and ecotoxicity impact potentials per tonne of output for the original DMUs (blue bars) and the virtual targets (purple bars)*

If a certain input had desirable effects on many categories, then it could be treated by DEA as an output so that the corresponding target resulted higher instead of lower and, therefore, the favourable effect would be obtained. Nevertheless, it is more likely that the contribution of an input is environmentally favourable in a specific category but unfavourable in all the rest. In that case, reducing the input, as DEA does, would help to decrease the environmental impacts in all categories except that one. What DEA allows (e.g. Thanassoulis & Dyson 1992) is that, instead of giving the same priority to all inputs reductions as in the objective function of models 8.1, 8.2 and 8.3, the reductions of the different inputs can be differently weighted by giving more priority to the reduction of those inputs that contribute more to the different environmental impact categories.

Figure 8.5 graphically shows how the target total environmental impact was lower than the current one for each of the impact categories.

As observed, important reductions are possible for all impact categories provided that the estimated operational inefficiencies are removed. The categories that would benefit most from the improvement in operational efficiency are ADP and ODP (around 20% improvement) followed by HTP, TETP and EP (around 10% improvement).

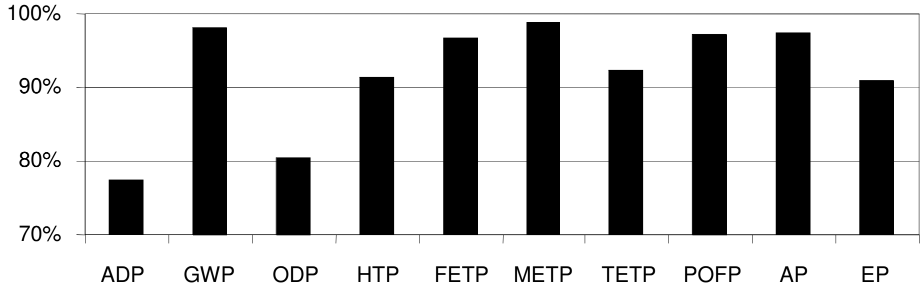


Figure 8.5. *Target versus current total environmental impact potentials*

Similarly, Figure 8.6 shows that the target total inputs consumption was generally lower than the current total. As shown, this is especially accurate for inputs I-2, I-3, I-4 and I-5, with estimated total reductions above 50%. These important inputs reductions were estimated just using the observed inputs and output data and extending to every DMU the best practices observed in the sample.

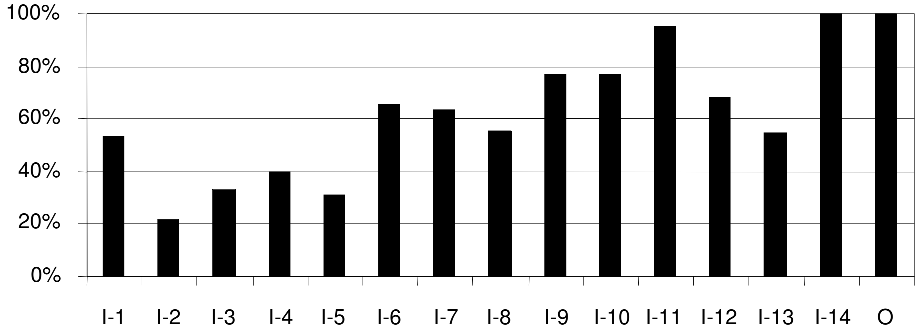


Figure 8.6. *Target versus current total inputs consumption*

Furthermore, in order to evaluate the influence of DMU size in the operational efficiency, Figure 8.7 shows the variation of the ERM-CRS efficiency score as a function of the output of the DMU. As observed, in general, large DMUs tend to be more efficient than small and medium size DMUs.

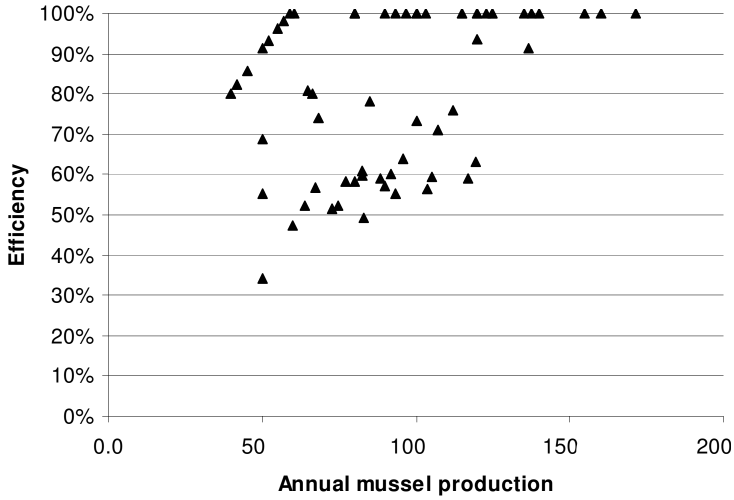


Figure 8.7. *Efficiency (%) versus size (annual tonnes of mussel)*

Finally, in order to further analyze the link between operational efficiency and environmental performance, Figure 8.8 shows the environmental improvement potential as a function of the ERM-CRS operational efficiency score.

According to Figure 8.8, the DMUs with lower operational efficiency are those that can reduce their environmental impacts by a larger amount. This observation proves that the efficiency of the ways in which the operations are carried out greatly influences the environmental impact of the processes.

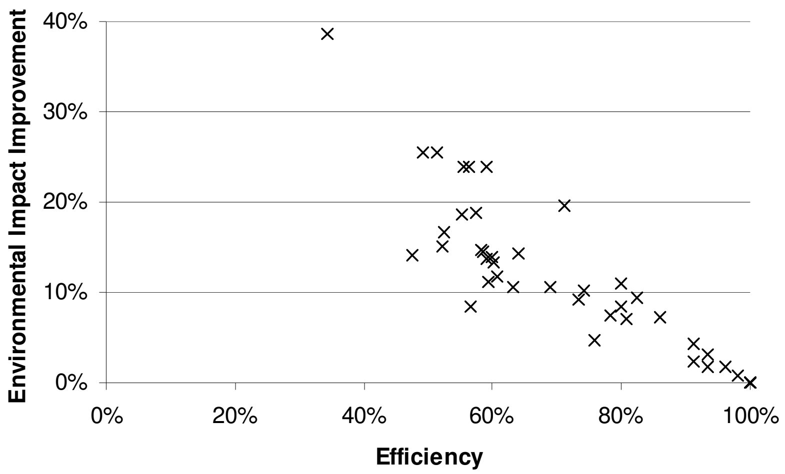


Figure 8.8. *Environmental impact improvement versus efficiency*

8.4. Conclusions

The combined application of LCA and DEA led to join the strengths and minimize the weaknesses attributable to both methodologies so that a synergistic effect was achieved while maintaining a quantitative character. The five-step LCA+DEA method proved to entail appealing characteristics, among which, the following are highlighted:

- Avoidance of the use of average inventories when assessing a high number of similar facilities. In this sense, undesirable standard deviations are prevented.
- Facilitation and enrichment of the interpretation of the results for multiple LCAs. The LCA+DEA method is not limited to environmental impacts but adds an economic dimension to the sustainability assessment.
- Means for eco-efficiency verification. The five-step LCA+DEA approach reveals the link between operational efficiency and environmental impacts, quantifying the environmental consequences of operational inefficiencies. The application of LCA to the virtual targets quantitatively verifies if the operational benchmarking leads to a better environmental performance.

The strength of the approach proposed comes from its quantitative character since it is able to set targets and quantify potential improvements. Throughout the case study of mussel culture, the direct link between operational efficiency and environmental impacts was proved. In this case, from a real world data set for 62 mussel cultivation sites, only 24 of them were deemed efficient. This allowed important input reductions (larger than 50% in some cases) which resulted in significant reductions in potential environmental impacts, up to 20%. Furthermore, the illustration showed that positive inputs (those that may contribute positively to the environmental performance) should be given a special consideration in the DEA study.

Finally, in spite of the usefulness of the proposed approach, it should be noted that all processes and systems have differences that cannot be easily modelled (e.g. differences in local conditions). This often requires more detailed process models to fully understand them. The proposed LCA+DEA framework is no substitute of this; it is rather a benchmarking attempt to find targets for performance improvement within a sector, targets that are computed from a sample of available operational data.

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Chapter 9

Environmental impact efficiency[1]

Summary

In Chapter 8, the combined application of LCA and DEA was proposed to assess operational efficiency and to evaluate the environmental consequences of removing the operational inefficiencies, by means of a five-step LCA+DEA method.

In this chapter, a second LCA+DEA approach is proposed. It is a three-step method that can be used to directly estimate targets for the potential environmental impacts. This environmental performance assessment method is rather general and can be used in other LCA studies where data are available for multiple similar DMUs.

The application of the three-step LCA+DEA method to mussel culture sites led to identify operational inefficiencies and to improve potential environmental impacts. In this case study, since data were available on a whole sample of 83 mussel cultivation rafts, an LCI and an LCIA were developed for each one separately and an efficiency analysis was performed to identify those rafts that have the best practices and therefore can serve as benchmarks for the rest. A Slacks Based Measure (SBM) of environmental impact efficiency was computed using DEA, taking into account both input consumption and the characterization values for ten conventional environmental impact categories. As a result, 34 of the cultivation sites were deemed efficient. For the inefficient sites, reduction targets were computed concerning input consumption and potential environmental impacts.

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[1] Lozano, S., Iribarren, D., Moreira, M.T., Feijoo, G. (2010). "Environmental impact efficiency in mussel cultivation". Resour Conserv Recy. DOI: 10.1016/j.resconrec.2010.04.004

Index

9.1. Introduction

One of the main difficulties in the use of LCA is the requirement of comprehensive data, which often leads to costly and lengthy data acquisition tasks. In LCA studies, it is common to evaluate a great number of facilities or installations in order to get a suitable set of representative data. The higher the number of inventoried facilities, the greater representativeness is expected but also a more difficult interpretation of the LCA results, especially when average values are not used because of data deviation. In this context, the complementary application of other management tools is useful. In the previous chapter, the combined application of LCA+DEA according to a five-step method proved to be a good choice when pursuing operational efficiency and eco-efficiency verification together with the avoidance of the use of average inventories. In this chapter, another LCA+DEA approach is presented in accordance with a three-step method which leads to an operational and environmental impact efficiency assessment.

The three-step LCA+DEA method is tested for mussel cultivation sites. In Chapter 3, an LCA study for mussel culture in Galician rafts was performed so that: (i) a representative raft and an average vessel were defined, (ii) a detailed inventory was obtained, (iii) characterization results were calculated for a set of ten environmental impact categories, and (iv) environmental hot spots were identified and potential improvement actions proposed. Therefore, this study relied on average values from a data set for multiple mussel cultivation rafts. Conversely, the current chapter suggests avoiding the use of average data by following the three-step LCA+DEA method with the aim of benchmarking the operational and environmental performance of mussel cultivation rafts. In this sense, the complementary use of DEA (Zhu 2001; Ramanathan 2003; Cooper et al. 2004, 2007) enables the identification of the efficient units along with the calculation of an efficiency score and target efficient points for those sites found inefficient. In fact, the single use of DEA has been proposed in the literature to undertake environmental performance analyses (e.g. Tyteca 1997; Zaim & Taskin 2000; Dyckhoff & Allen 2001; Korhonen & Luptacik 2004; Kuosmanen & Kortelainen 2005, 2007; Zhou et al. 2006, 2007; Munksgaard et al. 2007; Lozano & Gutiérrez 2008).

The LCA+DEA approach for mussel farming can help skippers and raft operators to be aware of wasteful practices and, therefore, of the need to reduce consumption levels in order to mitigate environmental impacts without reducing production levels.

9.2. LCA+DEA framework

The goal of this chapter is to propose and apply an LCA+DEA approach that determines operational and environmental efficiency, and which directly estimates operational and environmental targets for the inefficient units.

9.2.1. The three-step LCA+DEA method

As summarized in Figure 9.1, the LCA+DEA methodology proposed in this chapter comprises three main steps:

i) LCI for each of the DMUs. This first stage involves input and output data collection for the units being assessed.

ii) LCIA for each of the DMUs from the LCI developed in the first step. This second phase consists in the environmental characterization of the current DMUs.

iii) DEA from the LCIs of the first step and the characterization values of the second step: Determination of the operational and environmental impact efficiency of each DMU and calculation of the target DMUs. Interestingly, this last step leads to the comparison of the current values with the corresponding target values for the different impact categories selected.

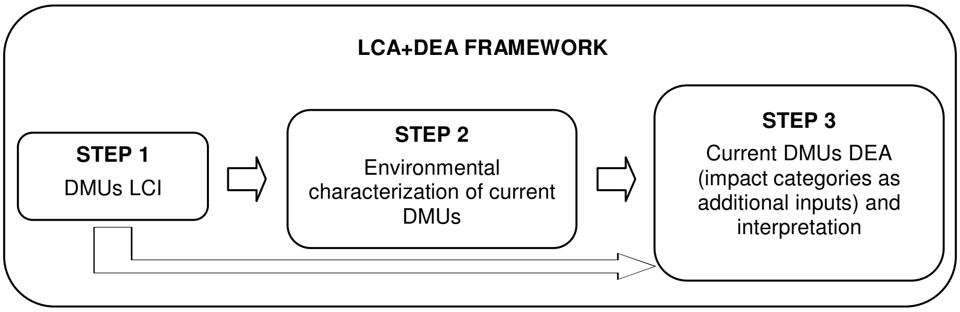


Figure 9.1. *Schematic representation of the three-step LCA+DEA method*

Unlike the five-step LCA+DEA method described in Chapter 8, the three-step method avoids the environmental characterization of the target DMUs by implementing environmental impact potentials as inputs when performing DEA in the third step. In other words, the third stage comprises a DEA with a higher number of inputs than the DEA of the five-step method given the consideration of the potential environmental impacts determined in the second step as inputs for the DEA along with the selected LCI inputs/outputs. In this sense, the benchmarking results directly estimate targets for both LCI inputs/outputs and the potential environmental impacts. The three-step LCA+DEA method is useful when seeking a quick preliminary operational and environmental benchmarking of a large number of entities.

With regard to DEA performance, it is important to recall the rule of thumb for the determination of the minimum sample size: $n \geq \max \{m \cdot s, 3 \cdot (m+s)\}$ (Cooper et al. 2007), where m is the number of inputs used in the DEA study and s is the number of outputs involved. The minimum sample size for the three-step method results in an increased number of DMUs to be assessed when compared to the five-step method, due to the higher number of inputs (m).

9.2.2. LCA summary

In this particular case, LCA aims to characterize mussel culture for 83 rafts from an environmental point of view in order to subsequently implement the characterization results into a DEA model for the efficiency assessment. As the case study of mussel culture has been previously detailed in Chapter 3, only a few key aspects are here remembered.

The different culture stages from collecting the seed to packaging prior to fresh mussel delivery were covered. Likewise, construction, operation and maintenance of rafts and vessels were included.

Data were obtained from individualized questionnaires that were answered by a significant number of skippers of auxiliary boats in charge of 83 rafts in the most representative area for mussel aquaculture in Galicia (Ria de Arousa). These questionnaires –as well as being the source for the LCIs– also allowed setting the values of input consumption which are necessary for DEA.

For the LCIA stage, the LCI of each of the 83 rafts was analyzed with the software SimaPro 7 (Goedkoop et al. 2008). CML was the environmental impact assessment method, involving the ten conventional impact categories used throughout this thesis: ADP, GWP, ODP, HTP, FETP, METP, TETP, POFP, AP and EP. The assessment of the potential environmental impact was conducted for each raft on the basis of a certain FU: the annual production of commercial size mussels. The results obtained for the environmental characterization were then used with the purpose of calculating the environmental impact efficiency of mussel culture once they were implemented into the DEA model that is detailed next within the DEA framework.

9.2.3. DEA framework

This DEA study considers as units of assessment (i.e., decision making units, DMUs) the mussel cultivation sites (rafts). The value of the main inputs that appear in the corresponding LCI and the LCIA characterization results were known for each DMU. The FU was the annual production of mussels of commercial size. Figure 9.2 shows the schematic representation of these variables.

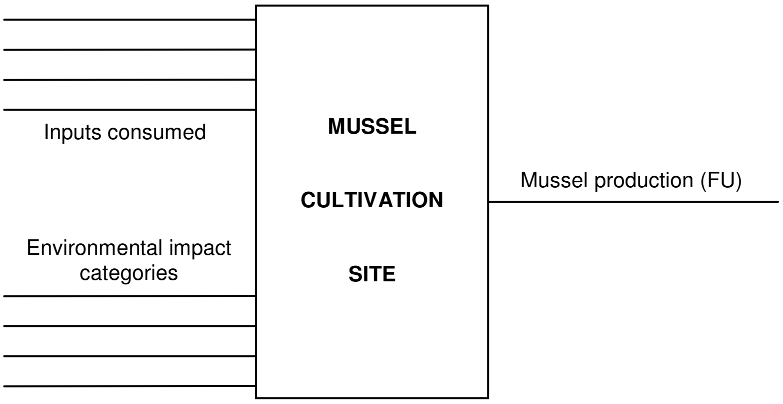


Figure 9.2. *Input-output model for the benchmarking of environmental impacts*

The selection of the main inputs for DEA is shown in Table 9.1. The selected inputs for the efficiency analysis included not only input consumption but also the ten environmental impact categories selected. The labels used throughout this chapter for these DEA inputs are also presented in Table 9.1 together with the corresponding units of measurement.

On the one hand, the quantification of input consumption arose from the LCI for each raft. On the other hand, the characterization values for the environmental impact categories came from the LCIA for each of the 83 rafts.

Table 9.1. *List of the inputs for the DEA of mussel culture*

Label	Inputs consumption	Units
IC1	Diesel B	l
IC2	Lubricating oil	l
IC3	Paint	l
IC4	Wastewater from auxiliary boat	l
IC5	Wood for auxiliary boat	kg
IC6	Iron for floats	kg
IC7	Iron for shackle chain	kg
IC8	Concrete for anchoring block	kg
IC9	Nylon	kg
IC10	Cotton	kg
IC11	Tar oil	l
IC12	Wood for raft	kg
IC13	High density polyethylene (HDPE) for plastic pegs	kg
IC14	Electricity for capital goods	GJ
Label	**Environmental impact categories**	**Units**
ADP	Abiotic Depletion Potential	kg Sb eq
GWP	Global Warming Potential	kg CO_2 eq
ODP	Ozone layer Depletion Potential	kg CFC-11 eq
HTP	Human Toxicity Potential	kg 1,4-DB eq
FETP	Fresh water aquatic Eco-Toxicity Potential	kg 1,4-DB eq
METP	Marine aquatic Eco-Toxicity Potential	kg 1,4-DB eq
TETP	Terrestrial Eco-Toxicity Potential	kg 1,4-DB eq
POFP	Photochemical Oxidant Formation Potential	kg C_2H_2 eq
AP	Acidification Potential	kg SO_2 eq
EP	Eutrophication Potential	kg PO_4^{3-} eq

The DEA model used for the study of the operational and environmental impact efficiency of mussel culture was the Slacks Based Measure (SBM) of efficiency model (Tone 2001). Before the formulation of this model, some notations need to be introduced:

- N → number of DMUs to benchmark
- j = 1, 2,..., N → index on the DMU
- M → number of different inputs consumed by the DMU

- C → number of impact categories from the LCIA
- $k = 1, 2, \ldots, M$ → index on inputs consumed
- $i = 1, 2, \ldots, C$ → index on environmental impact categories
- x_{kj} → amount of input k consumed by DMU j
- z_{ij} → characterization value of impact category i for DMU j
- y_j → functional unit used in the LCA of DMU j
- 0 → index of the DMU being assessed
- $(\lambda_{10}, \lambda_{20}, \ldots, \lambda_{N0})$ → vector of coefficients of linear combination for assessing unit 0
- σ_{k0} → slack (i.e., potential reduction) in the consumption of input k by DMU 0
- s_{i0} → slack (i.e., potential reduction) of impact category i for DMU 0
- ρ_0 → slack (i.e., potential increase) of output for DMU 0
- ξ_0 → impact efficiency for DMU 0

SBM model

$$\xi_0 = \mathrm{Min} \quad \frac{1 - \frac{1}{M+C}\left(\sum_{k=1}^{M} \frac{\sigma_{k0}}{x_{k0}} + \sum_{i=1}^{C} \frac{s_{i0}}{z_{i0}}\right)}{1 + \frac{\rho_0}{y_0}} \qquad \text{(Model 9.1)}$$

subject to

$$\sum_{j=1}^{N} \lambda_{j0} x_{kj} = x_{k0} - \sigma_{k0} \quad \forall k$$

$$\sum_{j=1}^{N} \lambda_{j0} z_{ij} = z_{i0} - s_{i0} \quad \forall i$$

$$\sum_{j=1}^{N} \lambda_{j0} y_j = y_0 + \rho_0$$

$$\lambda_{j0} \geq 0 \ \forall j \quad \sigma_{k0} \geq 0 \ \forall k \quad s_{i0} \geq 0 \ \forall i$$

The objective function of Model 9.1 is non linear, although it can be easily linearized as explained in Tone (2001). It represents the ratio of the average reduction in the inputs consumed and in the potential impacts generated by DMU 0 to the increase in output. This type of model tries to find a feasible operating point that consumes reduced amounts of input, entails lower environmental impacts and produces more output than the current DMU 0. If it succeeds, then ξ_0 is lower than 1. Otherwise, if it is not feasible to reduce the consumption of any input, to reduce the potential impact in any category or to increase the output, then $\xi_0 = 1$ (because $\rho_0 = 0 \quad \sigma_{k0} = 0 \quad \forall k \quad s_{i0} = 0 \quad \forall i$) and DMU 0 is deemed efficient.

In addition to the environmental impact efficiency ξ_0, this model allows the computation of targets:

$$\hat{x}_{k0} = \sum_{j=1}^{N} \lambda_{j0} x_{kj} = x_{k0} - \sigma_{k0} \quad \forall k \qquad \text{(Equation 9.1)}$$

$$\hat{z}_{i0} = \sum_{j=1}^{N} \lambda_{j0} z_{ij} = z_{i0} - s_{i0} \quad \forall i \qquad \text{(Equation 9.2)}$$

$$\hat{y}_0 = \sum_{j=1}^{N} \lambda_{j0} y_j = y_0 + \rho_0 \qquad \text{(Equation 9.3)}$$

These equations define the target values for input consumption levels, potential environmental impacts and output production that could be achieved by DMU 0 if it were efficient. These targets should be used by DMU 0 to guide its improvement efforts towards environmental impact efficiency. In other words, DMU 0 should be asked to reduce its consumption of each input k by an amount σ_{k0} and its potential environmental impact for every category i by an amount s_{i0}, and at the same time DMU 0 would increase its associated output by an amount ρ_0. In this way, the DMU would be efficient and would be operating on the efficient frontier. Note that DEA computes the efficient frontier on the basis of the observed data. The only implicit assumptions in Model 9.1 with respect to the feasible PPS are (i) convexity, (ii) constant returns to scale (CRS), and (iii) free disposability of inputs and outputs.

9.3. Application to mussel cultivation sites

Table 9.2 shows some descriptive statistics of the sample. Values in Table 9.2 refer to the production of 1 tonne of commercial size mussels. Note that IC14 is constant because the consumption of that input was estimated as a fixed amount per unit of production.

Table 9.2. *Descriptive statistics for the data set of the 83 DMUs*

Variable	Min	Max	Mean	Standard deviation
IC1	4.000	350.000	54.732	72.629
IC2	0.056	5.000	0.785	1.023
IC3	0.041	1.000	0.207	0.163
IC4	0.198	6.682	1.360	1.734
IC5	0.727	20.548	2.760	2.368
IC6	5.242	37.986	14.397	6.403
IC7	0.519	3.759	1.480	0.633
IC8	4.500	40.000	14.964	8.384
IC9	2.173	6.272	3.751	1.323
IC10	0.217	0.639	0.386	0.135
IC11	0.212	10.870	1.951	2.062
IC12	16.667	118.689	39.831	21.111
IC13	0.157	0.812	0.354	0.147
IC14	2.700	2.700	2.700	0.000
ADP	0.326	1.621	0.766	0.268
GWP	318.841	1,371.864	505.319	212.711
ODP	$3.393 \cdot 10^{-5}$	$1.327 \cdot 10^{-3}$	$2.310 \cdot 10^{-4}$	$2.691 \cdot 10^{-4}$
HTP	121.586	526.306	181.605	77.419
FETP	37.563	120.694	49.499	17.438
METP	506,999.851	1,809,340.234	668,955.150	282,374.007
TETP	0.691	1.711	0.871	0.171
POFP	0.212	0.518	0.256	0.064
AP	5.526	20.556	7.678	3.151
EP	0.253	2.483	0.595	0.465

Table 9.3 shows the SBM environmental impact efficiency ξ_0 and the potential reductions for the environmental impact categories, while Table 9.4 gathers the potential reductions for the input consumption levels.

Table 9.3. *Environmental impact efficiency and potential reduction (%) in environmental impacts*

DMU	ξ_0 (%)	s_{i0}/z_{i0} (%)									
		ADP	**GWP**	**ODP**	**HTP**	**FETP**	**METP**	**TETP**	**POFP**	**AP**	**EP**
1	73.07	30.79	0.00	36.52	12.28	3.78	1.45	0.00	1.24	0.96	10.79
2	83.86	11.45	0.82	16.48	10.25	1.43	0.35	6.67	0.94	1.37	6.03
3	75.58	40.20	0.00	37.55	12.65	7.44	2.99	8.29	5.40	3.51	14.55
4	74.47	42.76	0.00	39.66	12.62	7.33	2.93	7.17	5.14	3.35	14.63
5	72.36	46.91	0.00	40.90	12.81	7.29	2.87	6.57	5.00	3.26	14.63
6	73.38	42.70	0.00	34.45	12.19	6.54	2.57	6.33	4.45	2.86	13.11
7	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
8	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
9	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
10	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
11	99.76	0.33	0.00	0.48	0.08	0.04	0.01	0.04	0.03	0.03	0.13
12	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
13	99.89	0.21	0.00	0.28	0.04	0.02	0.01	0.02	0.01	0.02	0.08
14	99.73	0.56	0.00	0.53	0.10	0.05	0.02	0.03	0.03	0.03	0.13
15	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
16	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
17	73.82	40.59	0.00	38.55	10.44	5.68	2.29	0.00	3.24	2.49	14.41
18	72.95	41.89	0.00	38.50	10.67	5.73	2.30	0.00	3.23	2.48	14.52
19	71.14	40.29	1.15	36.65	10.43	5.44	2.22	0.53	3.27	2.73	16.46
20	71.81	39.03	1.59	36.36	9.76	5.06	2.06	0.74	3.14	2.81	16.48
21	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
22	99.13	1.60	0.00	1.48	0.60	0.34	0.14	0.20	0.22	0.16	0.66
23	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
24	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
25	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
26	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
27	75.27	49.21	11.04	60.25	12.87	3.56	1.05	11.10	4.52	8.14	28.05

Table 9.3. *Environmental impact efficiency and potential reduction (%) in environmental impacts (cont.)*

DMU	**ξ_0 (%)**	**s_{i0}/z_{i0} (%)**									
		ADP	**GWP**	**ODP**	**HTP**	**FETP**	**METP**	**TETP**	**POFP**	**AP**	**EP**
28	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
29	62.06	63.28	3.57	61.35	27.59	12.45	4.74	13.85	8.34	7.73	28.29
30	64.57	59.32	8.15	62.10	22.98	9.38	3.40	14.68	7.45	8.67	30.37
31	65.04	58.44	10.42	63.60	21.04	8.33	2.98	15.22	7.38	9.37	32.45
32	67.93	41.59	5.07	52.12	22.74	4.45	1.24	12.65	3.18	5.79	23.01
33	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
34	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
35	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
36	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
37	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
38	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
39	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
40	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
41	99.99	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01
42	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
43	72.38	32.32	0.00	27.33	14.33	6.60	2.60	10.54	4.70	2.89	13.16
44	74.21	29.02	1.82	31.59	11.35	3.44	1.18	7.70	2.55	2.48	11.08
45	66.75	51.14	0.00	52.97	22.83	8.37	3.17	8.25	4.44	3.43	19.68
46	70.12	43.50	0.00	38.94	22.66	7.03	2.46	12.35	4.10	3.29	15.11
47	73.34	36.99	1.10	33.12	21.63	5.72	1.85	14.48	3.77	3.48	13.63
48	60.50	59.91	6.78	61.16	29.81	10.86	3.88	18.40	7.82	8.58	30.26
49	66.15	60.07	14.07	73.05	21.31	6.65	2.07	19.20	7.25	11.03	35.54
50	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
51	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
52	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
53	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
54	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
55	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
56	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*

Table 9.3. *Environmental impact efficiency and potential reduction (%) in environmental impacts (cont.)*

DMU	**ξ_0 (%)**	**s_{i0}/z_{i0} (%)**									
		ADP	**GWP**	**ODP**	**HTP**	**FETP**	**METP**	**TETP**	**POFP**	**AP**	**EP**
57	81.18	22.70	2.20	26.71	7.04	2.11	0.84	1.85	1.47	2.11	13.20
58	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
59	47.06	76.66	15.90	77.66	43.26	20.18	8.02	27.55	15.41	16.88	49.32
60	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
61	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
62	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
63	53.81	52.94	42.58	88.21	45.78	37.99	41.90	15.88	27.13	41.99	69.17
64	54.62	52.62	42.31	88.09	45.23	37.52	41.44	15.35	26.71	41.66	68.92
65	56.95	52.59	42.36	88.14	44.39	36.91	40.92	14.81	26.18	41.59	68.87
66	60.48	53.39	41.86	87.65	43.37	36.61	40.57	14.45	25.90	41.41	68.13
67	64.05	47.00	39.98	83.78	41.39	34.91	39.00	14.80	24.75	39.95	65.35
68	80.57	25.17	21.23	44.54	22.21	18.68	20.84	7.89	13.22	21.25	34.75
69	*100.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
70	32.71	66.29	52.02	92.04	64.87	55.55	58.32	36.83	44.95	54.82	78.71
71	33.38	65.84	52.62	92.10	64.02	54.77	57.73	35.76	44.15	54.85	78.82
72	34.56	64.97	52.61	91.99	62.63	53.44	56.56	34.05	42.79	54.31	78.56
73	35.55	64.47	53.05	92.01	61.70	52.60	55.90	32.92	41.93	54.25	78.60
74	38.11	63.43	53.58	91.99	59.78	50.89	54.50	30.64	40.20	53.94	78.55
75	38.46	63.29	53.58	91.97	59.54	50.67	54.31	30.37	39.99	53.86	78.51
76	27.64	76.38	70.86	95.01	76.36	68.88	71.98	53.93	58.54	71.11	87.21
77	39.88	61.83	53.58	91.65	57.87	49.33	53.10	28.41	38.42	52.56	77.44
78	41.91	61.30	53.46	91.60	56.83	48.42	52.33	27.22	37.52	52.30	77.33
79	43.97	60.99	53.54	91.62	56.12	47.83	51.88	26.43	36.93	52.27	77.37
80	45.41	64.95	53.43	92.27	55.41	47.71	51.59	28.83	37.25	52.69	77.21
81	47.44	60.50	51.47	89.27	53.91	47.50	51.37	23.29	36.07	51.22	74.92
82	34.13	71.88	67.37	95.09	69.63	62.23	66.16	42.77	51.64	66.26	85.74
83	35.45	71.76	65.96	93.74	68.59	62.42	66.15	40.89	51.41	65.66	84.25
Average	54.73	32.96	21.90	67.12	27.43	20.30	22.07	11.80	14.30	22.15	44.67

Table 9.4. *Potential reduction (%) in input consumption*

DMU	σ_{k0}/x_{k0} (%)													
	IC1	**IC2**	**IC3**	**IC4**	**IC5**	**IC6**	**IC7**	**IC8**	**IC9**	**IC10**	**IC11**	**IC12**	**IC13**	**IC14**
1	49.99	66.90	52.64	71.59	72.38	20.72	20.72	33.20	15.59	15.59	71.33	14.88	43.01	0.00
2	22.86	17.35	64.13	78.48	72.95	1.41	1.41	23.74	8.19	8.19	23.97	0.00	8.82	0.00
3	47.74	58.41	0.00	44.51	49.87	38.61	39.63	45.14	17.21	17.21	43.66	36.45	15.04	0.00
4	50.44	59.43	0.00	45.36	50.35	40.99	41.98	47.29	16.86	16.86	47.59	38.92	20.99	0.00
5	51.19	59.85	0.63	45.84	50.74	46.39	47.28	52.35	16.81	16.81	63.75	44.51	26.89	0.00
6	42.32	59.54	14.41	48.45	54.83	44.01	44.94	49.97	18.92	18.93	50.09	42.04	25.33	0.00
7	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
8	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
9	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
10	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
11	0.69	0.69	0.69	0.69	0.69	0.20	0.20	0.20	0.00	0.00	0.20	0.20	0.20	0.00
12	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
13	0.40	0.32	0.00	0.25	0.19	0.12	0.12	0.13	0.00	0.00	0.23	0.12	0.08	0.00
14	0.71	0.55	0.00	0.43	0.33	0.49	0.49	0.50	0.00	0.00	0.71	0.49	0.41	0.00
15	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
16	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
17	45.82	80.00	0.00	46.95	69.55	37.64	37.64	38.08	15.16	13.61	55.68	37.67	32.85	0.00
18	45.48	79.10	3.94	48.06	70.06	40.01	40.01	40.40	16.65	15.13	53.95	40.12	36.85	0.00
19	43.25	80.75	18.94	50.01	72.55	38.18	38.18	38.18	29.17	29.17	48.48	38.18	48.48	0.00
20	43.13	80.70	18.76	49.90	72.49	35.80	35.80	35.80	29.17	29.17	46.50	35.80	46.50	0.00
21	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
22	1.65	1.98	0.00	1.47	1.35	1.60	1.60	1.76	0.42	0.42	0.00	1.60	1.52	0.00
23	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
24	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
25	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
26	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
27	68.85	35.56	63.55	72.55	66.04	5.85	5.85	0.00	2.87	2.87	49.42	10.55	19.89	0.00
28	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
29	67.99	80.99	79.99	82.05	72.27	60.35	60.35	53.74	2.96	0.00	15.03	60.35	43.35	0.00
30	69.67	80.70	75.17	80.93	69.27	48.47	48.47	40.10	14.01	12.89	0.00	48.47	35.79	0.00
31	71.69	80.55	70.28	79.91	66.36	42.29	42.29	33.19	22.49	22.49	0.00	42.29	35.96	0.00
32	60.39	83.11	86.67	65.11	75.77	0.00	33.33	61.01	9.30	7.65	50.74	28.39	36.46	0.00

Table 9.4. *Potential reduction (%) in input consumption (cont.)*

DMU	σ_{k0}/x_{k0} (%)													
	IC1	**IC2**	**IC3**	**IC4**	**IC5**	**IC6**	**IC7**	**IC8**	**IC9**	**IC10**	**IC11**	**IC12**	**IC13**	**IC14**
33	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
34	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
35	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
36	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
37	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
38	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
39	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
40	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
41	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.03	0.01	0.01	0.00	0.01	0.03	0.00
42	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
43	35.58	85.54	39.88	63.93	66.05	31.90	33.03	39.80	27.56	27.56	59.25	27.67	10.71	0.00
44	44.20	87.48	47.92	68.75	70.59	22.11	23.41	31.15	15.16	15.16	60.39	17.28	13.20	0.00
45	65.90	92.04	65.90	15.88	48.64	43.72	43.72	26.41	24.22	24.22	76.08	44.75	52.17	0.00
46	47.12	77.18	74.85	37.98	51.30	42.45	42.45	30.66	18.81	18.81	43.81	46.50	35.70	0.00
47	40.17	71.51	78.63	47.29	52.80	36.00	36.00	26.15	16.67	16.67	20.00	42.16	20.00	0.00
48	68.26	88.75	88.16	76.31	82.23	51.63	51.63	55.24	16.67	16.67	11.70	51.63	51.63	0.00
49	83.25	87.75	64.99	64.99	67.05	24.92	24.92	32.50	5.45	5.46	61.17	24.92	14.91	0.00
50	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
51	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
52	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
53	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
54	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
55	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
56	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
57	33.95	60.57	51.41	33.95	49.90	9.75	9.75	18.02	27.91	27.91	0.00	19.03	29.24	0.00
58	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
59	82.61	95.87	91.30	82.61	90.55	69.89	69.89	56.09	35.90	35.90	70.86	67.29	70.86	0.00
60	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
61	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
62	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
63	92.57	97.06	62.87	95.42	42.36	33.57	33.57	53.50	11.62	10.00	46.85	13.39	52.17	0.00
64	92.50	97.03	62.49	95.37	41.77	30.94	30.94	51.66	11.62	10.00	44.76	9.97	50.28	0.00

Table 9.4. *Potential reduction (%) in input consumption (cont.)*

DMU	σ_{k0}/x_{k0} (%)													
	IC1	**IC2**	**IC3**	**IC4**	**IC5**	**IC6**	**IC7**	**IC8**	**IC9**	**IC10**	**IC11**	**IC12**	**IC13**	**IC14**
65	92.55	96.48	60.50	95.41	39.24	22.94	22.94	46.50	10.14	8.50	38.95	0.00	42.38	0.00
66	92.04	91.64	39.71	95.09	11.49	22.49	22.48	47.60	1.79	0.00	42.33	0.00	28.56	0.00
67	88.25	89.81	45.91	90.83	0.00	12.46	15.81	42.15	1.74	0.00	34.52	0.00	10.44	0.00
68	46.87	47.70	24.31	48.25	0.00	7.42	9.36	24.90	0.93	0.00	20.41	0.00	6.31	0.00
69	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
70	94.99	95.46	79.54	64.67	70.36	78.55	78.55	79.15	60.72	60.00	89.28	78.66	80.70	0.00
71	95.04	95.51	79.75	65.02	70.66	76.07	76.07	76.73	60.72	60.00	88.03	76.19	78.46	0.00
72	94.98	95.45	79.50	64.60	70.30	72.65	72.65	73.41	60.72	60.00	86.32	72.79	75.38	0.00
73	95.00	95.48	79.61	64.80	70.47	68.92	68.92	69.78	60.72	60.00	84.46	69.08	72.03	0.00
74	95.01	95.49	79.65	64.86	70.52	59.29	59.29	60.42	60.72	60.00	79.64	59.49	63.36	0.00
75	95.00	95.48	79.61	64.80	70.47	58.04	58.04	59.21	60.72	60.00	79.02	58.25	62.24	0.00
76	96.58	93.16	82.91	89.46	90.62	79.62	79.62	75.54	52.86	52.00	91.67	52.45	70.00	0.00
77	94.80	97.65	75.23	95.42	81.54	56.29	56.29	61.76	50.90	50.00	56.29	28.78	73.78	0.00
78	94.78	97.64	75.13	95.40	81.47	49.30	49.30	55.64	50.90	50.00	49.30	17.38	69.58	0.00
79	94.80	97.65	75.23	95.42	81.54	41.72	41.72	49.01	50.90	50.00	41.73	5.03	65.03	0.00
80	95.33	91.10	55.48	95.88	69.47	45.00	45.00	58.75	38.62	37.50	54.17	17.50	45.00	0.00
81	92.54	85.79	28.96	93.43	51.29	52.00	52.00	56.80	41.08	40.00	60.00	16.00	52.00	0.00
82	97.00	98.73	82.11	96.69	86.67	58.92	58.92	64.05	55.81	55.00	67.13	10.73	70.42	0.00
83	95.70	92.33	48.84	95.27	64.92	70.19	70.19	73.17	46.97	46.00	80.12	30.44	64.22	0.00
Average	74.52	75.65	49.44	68.22	46.59	29.64	29.03	27.23	18.94	18.43	50.30	26.23	28.07	0.00

As highlighted in italics in tables 9.3 and 9.4, 34 out of the 83 cultivation sites were deemed efficient ($\xi_0 = 100\%$). The optimal potential output increases are not included because they were always zero, $\rho_0 = 0$.

As shown in Table 9.3 as well as in Figure 9.3, the potential environmental burdens for the ten impact categories might be significantly reduced in most cases. This analysis revealed that the categories affected most by operational inefficiencies were ODP and, somewhat less, EP. On the contrary, the categories affected least by operational inefficiencies were TETP and POFP.

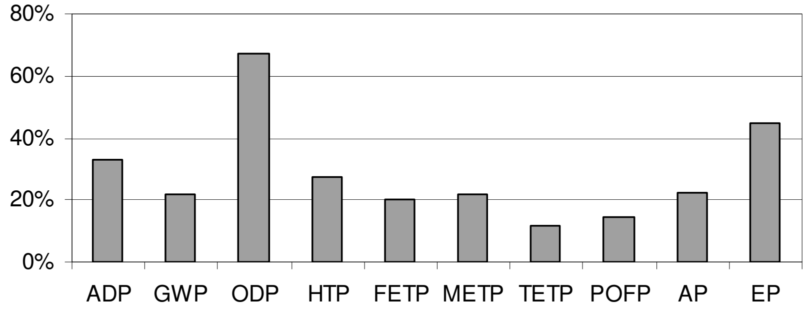


Figure 9.3. *Total percentage reduction in potential environmental impacts*

With respect to input consumption, Table 9.4 and Figure 9.4 suggest that those inputs that might be reduced most are IC2, IC1 and IC4 followed by IC11, IC3 and IC5. In contrast, for IC14 no reduction was possible for any DMU. This means that this input could have been omitted from the analysis. However, it was kept because maybe, in the future, a more accurate estimate for such input consumption will be available not being a fixed amount per unit of output.

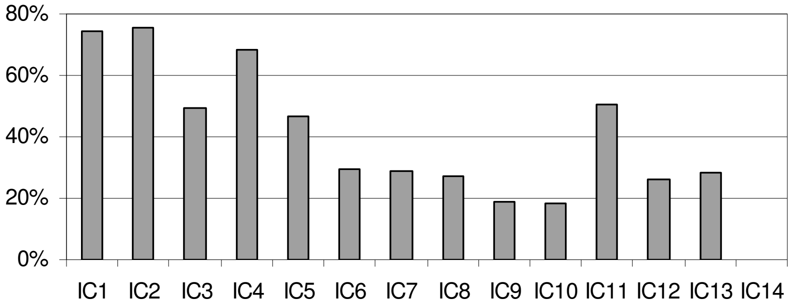


Figure 9.4. *Total percentage reduction in input consumption*

Furthermore, two different plots are proposed to present the results for each DMU. The first option involves the graphical representation of the percentage reduction in input consumption levels and environmental impacts that should be accomplished for each of the DMUs. Figure 9.5 is an example of this type of graphs. It represents percentage reductions concerning DMU 1. Reductions varied for the different operational inputs and also for the different impact categories. As shown in the case of DMU 1, they were generally larger for input consumption.

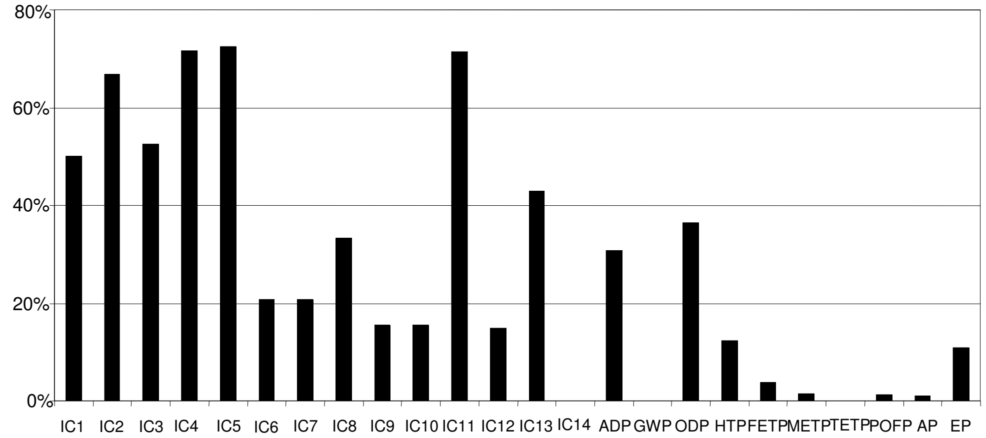


Figure 9.5. *Percentage reduction in input consumption levels and environmental impacts for DMU 1*

The second type of plots is exemplified by Figure 9.6, also for DMU 1. This graph shows, for each input consumption and environmental impact category, the efficient target computed as a fraction of the current value: $\frac{\hat{x}_{k0}}{x_{k0}}$ and $\frac{\hat{z}_{i0}}{z_{i0}}$. Although some operational inputs might be drastically reduced, the estimated environmental reductions were much smaller.

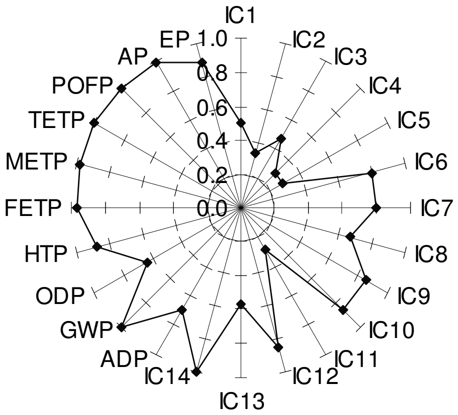


Figure 9.6. $\frac{\hat{x}_{k0}}{x_{k0}}$ *and* $\frac{\hat{z}_{i0}}{z_{i0}}$ *for DMU 1*

In addition to the individual analyses proposed for each of the DMUs, there are more options. For example, Figure 9.7 shows the percentage reductions in each environmental impact category for all the DMUs under study.

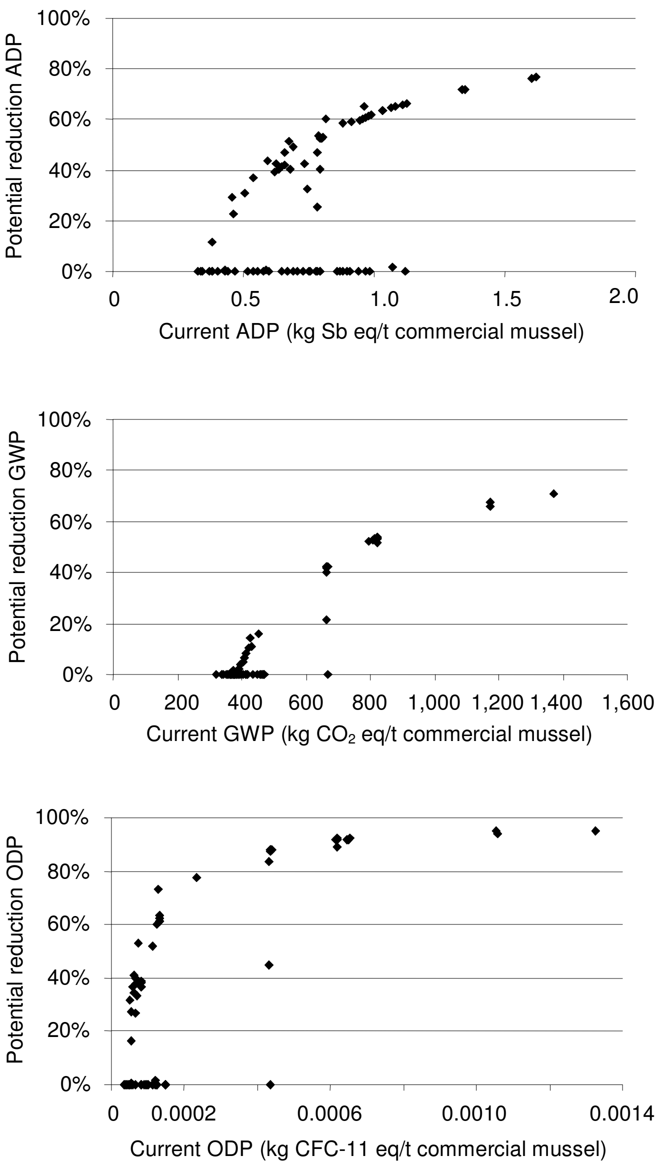


Figure 9.7. *Percentage reduction in potential environmental impacts for the different DMUs*

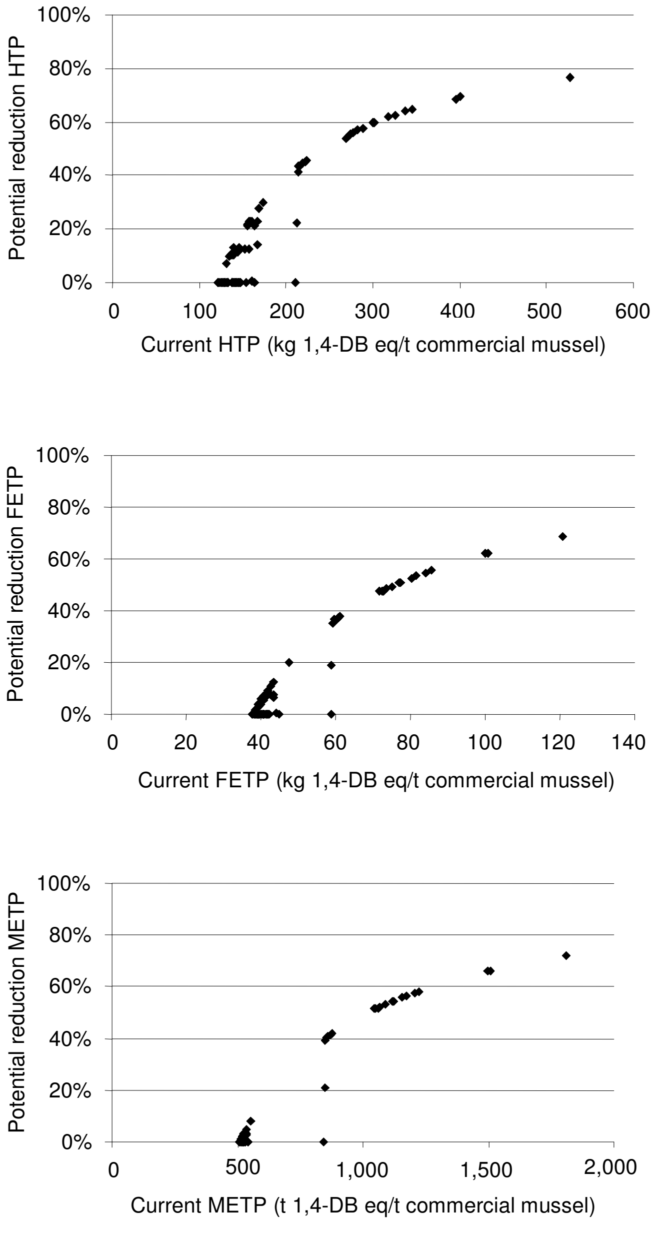
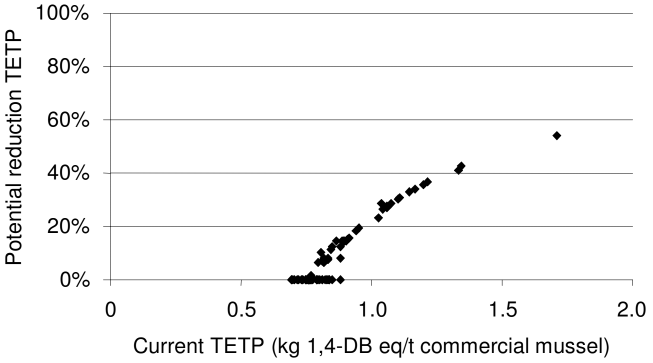
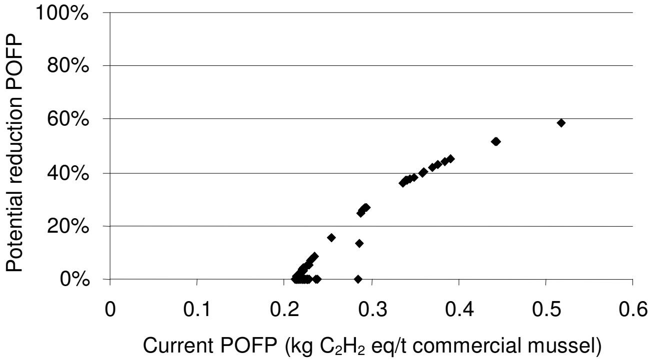


Figure 9.7. *Percentage reduction in potential environmental impacts for the different DMUs (cont.)*





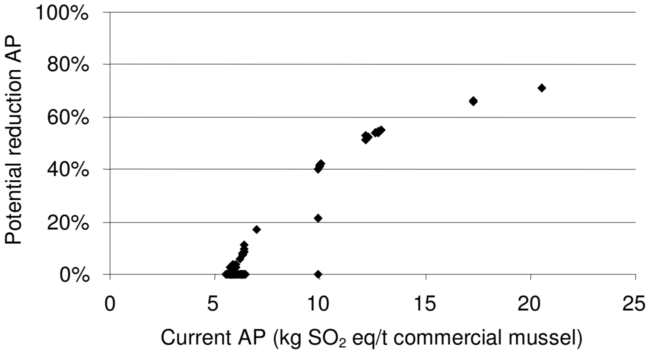


Figure 9.7. *Percentage reduction in potential environmental impacts for the different DMUs (cont.)*

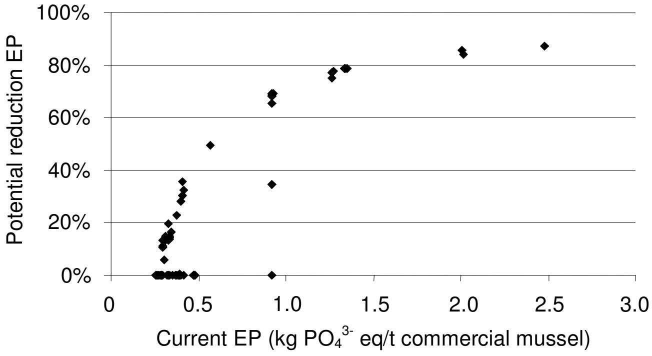


Figure 9.7. *Percentage reduction in potential environmental impacts for the different DMUs (cont.)*

As observed in Figure 9.7, the largest environmental impact reductions were generally associated with those DMUs that accounted for the largest current impacts. As the current value of the potential environmental impact of a DMU decreased, so did its margin for potential reduction. This pattern was found rather consistent among the different impact categories.

9.4. Conclusions

In this chapter, the combined application of LCA and DEA was proposed to evaluate environmental impact efficiency according to the three-step LCA+DEA method. Its use for mussel cultivation sites proved to enrich the interpretation and discussion of the LCA results for mussel aquaculture.

The three-step method enabled the environmental impact efficiency analysis of a set of 83 mussel rafts. An SBM model was developed to perform DEA. Data required for implementation into the DEA model were previously computed by means of LCA. The rationale behind the proposal of an LCA+DEA methodology was that the operational inefficiencies in the observed data lead to higher input consumption levels and greater environmental impacts than necessary. Therefore, the identification and removal of those inefficiencies would result in substantial improvements.

Inefficiencies were found in 49 of the 83 rafts. Average environmental impact efficiency was 55%. Furthermore, target input consumption levels and environmental impacts were computed for each mussel cultivation site. For the whole sample, the estimated reduction potential for a selection of environmental impact categories ranged from 11% for TETP to 67% for ODP. Moreover, total potential reductions in most input consumptions were highly significant (up to 75% in some cases). In general, the rafts for which the largest potential reductions were found were those that accounted for the largest current input consumption levels and potential environmental impacts.

This approach to assess the operational and environmental performance of multiple similar units can be used at a general scale for other LCA studies to compute environmental impact efficiency and benchmark input consumption levels and potential environmental impacts. The essential requirement is to have data on a sample of DMUs large enough for DEA to have reasonable discriminant power. Additionally, the number of inputs whose consumption is considered should not be excessively large.

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Chapter 10

Assessment of the carbon footprint[1]

Summary

Carbon Footprinting (CF) should not be understood as a mere LCA restricted to the global warming impact category. The increasing demand for environmental information on the global warming impact of products requires a solid methodological framework which guarantees comparability and communicability. The publicly available specification PAS 2050 combines approaches to a variety of GHG specific assessment issues to deliver a globally applicable product CF method, which is expected to be widely accepted.

This chapter uses the mussel case study to demonstrate the implementation of a CF scheme for a common canned mussel product according to PAS 2050 guidelines. Throughout this assessment, CF opportunities and drawbacks are discussed. Chapter 10 tries to provide a starting point for both mussel processors and policy makers to benefit from the potential advantages of a responsible use of this increasingly popular tool.

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[1] Iribarren, D., Hospido, A., Moreira, M.T., Feijoo, G. (2010). "Carbon footprint of canned mussels from a business-to-consumer approach. A starting point for mussel processors and policy makers". Environ Sci Policy. DOI: 10.1016/j.envsci.2010.05.003

Index

10.1. Introduction

The increasing awareness of climate change as a global concern has led stakeholders to demand a standard procedure to measure and communicate GHG emissions linked to consumer products. In this context, Carbon Footprinting (CF) has raised as an environmental tool, not only for companies along the product chain, but also for policy makers.

10.1.1. Carbon Footprinting and Life Cycle Assessment

CF involves the estimation of the overall amount of GHG emissions associated with a product (i.e., any good or service) along its supply chain, even including use and end-of-life recovery and disposal (EPLCA 2007). The final value for this estimate is known as product carbon footprint.

As defined in Chapter 2 and in accordance with Carbon Trust et al. (2008), “the term ‘product carbon footprint’ refers to the GHG emissions of a product across its life cycle, from raw materials through production (or service provision), distribution, consumer use and disposal/recycling. It includes the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), together with families of gases including hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs)”. Traditionally, product carbon footprints are quantified using life cycle impact indicators for the global warming mid-point category. In this sense, CF opponents understand this tool just as a subset of the data covered by a more complete LCA.

However, the use of carbon footprints for communication purposes questions the aptitude of the existing ISO standards (ISO 2006a, 2006b) to address the environmental impacts due to GHG emissions from products in a consistent and comprehensive way (SETAC 2008). Therefore, despite the existence of undeniable links between LCA and CF, the emergent methodological framework for the latter makes CF more than a mere LCA restricted to the global warming impact category.

Standardization efforts are necessary to provide guidance for people interested in quantifying the carbon footprint of a product. Within this framework, several initiatives have originated to meet the increasing market demand for climate relevant information along supply chains (Finkbeiner 2009). These initiatives have arisen mainly from prestigious institutions, such as the International Organization for Standardization (ISO), the World Business Council for

Sustainable Development (WBCSD) together with the World Resources Institute (WRI), the UNEP/SETAC Life Cycle Initiative, the British Standards Institution (BSI), the Japanese Ministry of Economy, Trade and Industry (METI), and the French Environment and Energy Management Agency (ADEME). Behind this stream of proposals is the involvement of high-profile retailers such as Tesco, Marks & Spencer or Carrefour, which are interested in implementing a CF scheme for their products.

In order to define a common standard for the assessment of GHG emissions associated with products (goods and services), the BSI, the Carbon Trust and the Department for Environment, Food and Rural Affairs (Defra, United Kingdom) started in 2007 a procedure that gave birth to the Publicly Available Specification 2050:2008 (BSI 2008), together with other complementary documents such as the Guide to PAS 2050 (Carbon Trust et al. 2008).

PAS 2050 specifies requirements for the assessment of the life cycle GHG emissions of goods and services based on key life cycle techniques and principles. Thus, PAS 2050 builds on the LCA guidance and requirements articulated in ISO 14040:2006 and ISO 14044:2006, adopting a life cycle approach to emissions assessment and the functional unit as the basis of any reporting (Sinden 2009). Furthermore, this specification also deals with other relevant methods and approaches in the field of GHG assessment such as ISO 14064 (ISO 2006c, 2006d, 2006e), IPCC publications (IPCC 2006, 2007) and the GHG Protocol (WRI/WBCSD 2004).

10.1.2. CF applications and implications

Direct applications of CF for companies include (Carbon Trust et al. 2008):

- Internal assessment of product life cycle GHG emissions and subsequent reduction.
- Incorporation of emissions impact into decision making regarding suppliers, materials, product design, manufacturing processes, etc.
- Support for corporate responsibility reporting.
- Identification of cost savings opportunities.
- Benchmarking for measuring and communicating emission reductions.
- Support for comparison of product-level GHG emissions.

Moreover, if a company decides to communicate the carbon footprint of any of its products, then customers become aware of how their purchasing decisions influence GHG emissions (Carbon Trust 2008). In this sense, communication is often used to gain market access and competitiveness.

Traditional environmental labelling schemes award an environmental label to those products that are judged to be less harmful to the environment than others within the same product group. To be awarded a label, a product has to meet a set of environmental criteria established for its product group by the labelling scheme organizer (Andersson 1998). These criteria relate to the complete product life-cycle. The use of LCA has proved to be suitable when analyzing the performance of food products to identify key environmental issues in support of the development of ecolabelling criteria (Mungkung et al. 2006). Furthermore, CF for food products is expected to boom due to the relevant contribution of food GHG emissions to global emissions (Garnett 2008, 2009).

Labelling should not be limited to the products considered least harmful, but it should cover all products. Therefore, in the near future, an additional role of policy makers could consist in encouraging global warming mitigation by promoting that economic actors within the food chain undertake CF schemes for their products according to a standardized procedure. This measure would foster the diffusion of life cycle thinking and LCA within firms, and could be the seed for a more consistent framework for the environmental assessment of products and services (Weidema et al. 2008). However, these schemes should not be used as a barrier for trading. For example, regarding developing countries, costly technical and organizational measures should be partially supported by stakeholders in the industrialized countries since they must be the main driver for the use of these schemes (Mungkung et al. 2006). Besides, the development of carbon labels for food products should also take into account the vulnerability of distant developing countries with a high level of substitutable exports. This vulnerability is the reason why developing countries accounting for substitutable food exports which demand long run transport identify CF as a current matter of concern (CF-Thailand 2008; Saunders & Barber 2008; Edwards-Jones et al. 2009). This concern is motivated by the retailers' desire of implementing CF schemes in the short term; in fact, retailers have arisen as the most determinant actor to extend the use of carbon footprints (Clift et al. 2005).

An example of the international interest in carbon labelling is that Planet Ark and the Carbon Trust have launched the Carbon Reduction Label in Australia in order to allow businesses, who independently verify the carbon footprints of their products, to communicate their carbon reduction commitment to their customers through an easy-to-understand label that appears on a product's packaging and other marketing material. The scheme aims to help companies reduce their costs and enhance their reputation through communicating their product carbon footprints (Planet Ark 2009).

Previous studies on the use of LCA in environmental policy suggest that LCA works better as a conceptual or facilitative instrument than as a tool for gaining definitive support for specific policies (Heiskanen 1999). In this regard, the current popularity of CF should not alter the nature of LCA, which is a tool rather than an all-encompassing solution. Otherwise, an inadequate use of LCA could lead to skewed policy decisions (Garnett 2008).

Within this context, this chapter develops the carbon footprint for a canned mussel product following the PAS 2050 method. This case study arises as a good example for policy makers to understand the opportunities provided by CF. Moreover, results facilitate the task of mussel processors to implement CF schemes into their commercial activities.

10.2. Justification and presentation of the case study

The goal of the current case study is to quantify the carbon footprint of the most common canned mussels' format: the triple pack of round cans.

As presented in Section II of this dissertation, the Galician mussel sector and, in particular, canned mussels' activities are of high relevance at regional, national and international scale. Galician rafts produce 98% of the mussels farmed in Spain. Not surprisingly, mussels (*Mytilus galloprovincialis*) are the single largest cultured shellfish in Galicia (Xunta de Galicia 2008). Fresh, canned and frozen mussels are the main mussel-based products. Specifically, 40% of the total production ends as canned mussels (Tirado & Macias 2006). Spanish canning factories obtain more than 90% of the mussel input from Galicia (MAPA 2007) and produce around 35,000 tonnes of canned mussels per year and a turnover of 66 million euros (Franco 2006).

Regarding product distribution, only 15% of the Galician mussel production is exported. In particular, France is the main foreign destination for Galician canned mussels, followed by Germany, Mexico, Portugal or the USA (Conde 2007). This figure does not suggest an export-based vulnerability to the development of carbon labels for mussel products. However, what is certainly highlighted as one of the major concerns within the Galician mussel sector is the threat of cheaper mussel products arriving from Chile (Estévez 2008). In this sense, the implementation of a CF scheme for the Galician mussel products could be adopted by regional mussel farmers and processors as a marketing strategy to reinforce their market position. This measure would answer the need for further product differentiation and would also anticipate future regulations on global warming.

10.3. Application to canned mussels

At this point in the chapter, the objective is to calculate the final value for the carbon footprint of the triple pack of round cans of mussels.

10.3.1. Method adopted for the CF of canned mussels

PAS 2050 was used as a reference method to conduct the CF of the triple pack of canned mussels. As shown in Figure 10.1, this specification distinguishes two different approaches for the assessment of life cycle GHG emissions for products (BSI 2008):

- The “cradle-to-grave” approach is named business-to-consumer (B2C) assessment. This implementation mode includes the emissions arising from the full life cycle of the product.
- The “cradle-to-gate” approach is named business-to-business (B2B) assessment. This mode comprises all upstream emissions and stops at the point where the product is delivered to a new organization.

The four basic steps to calculate the carbon footprint of any good or service include (Carbon Trust et al. 2008): (i) building a process map, (ii) checking boundaries and prioritization, (iii) collecting data, and (iv) calculating the carbon footprint. There is an optional final step where technical uncertainty is checked in order to improve confidence in footprint comparisons and in any decisions that are made based on the footprint.

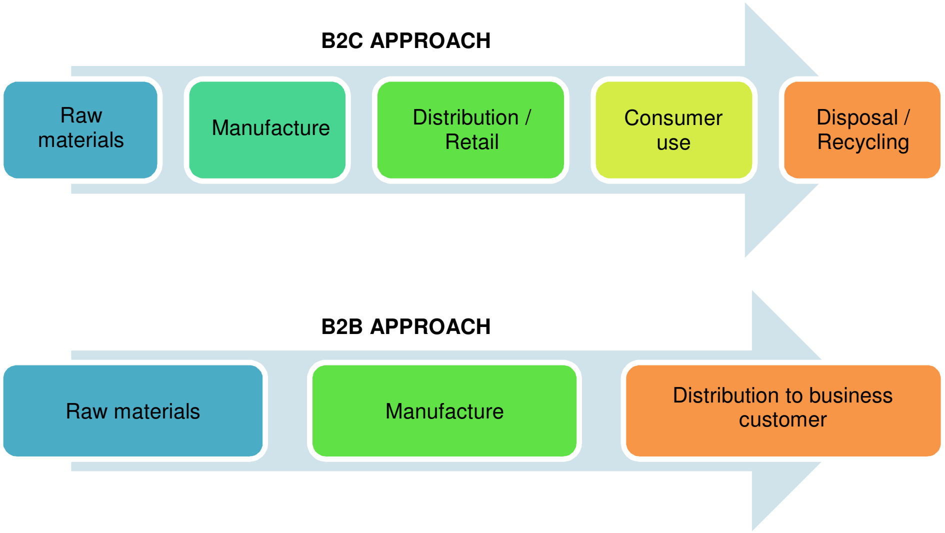

Figure 10.1. *Approaches for CF (adapted from Carbon Trust et al. 2008)*

10.3.2. Calculation of the carbon footprint for canned mussels

First of all, the CF approach must be selected. In this sense, unless the target good is used as an input to multiple final products with a wide range of uses and disposal characteristics, a B2C approach is preferred to a B2B assessment because of its comprehensive nature. Consequently, a B2C approach should be followed for canned mussels and, in general, for food products.

Building a process map

The first step pursues the identification of all materials, activities and processes which give rise to the life cycle GHG emissions associated with the target product. The building of a process map, as exhaustive as possible to include all possible drivers of GHG emissions, helps to achieve this goal.

In the first place, the product and the functional unit are defined. Most canned mussels are usually presented to the consumer under a triple pack of round cans format. Hence, the FU is one triple pack of round cans of canned mussels, made up of 129 g of canned mussel flesh, 120 g of sauce, 81 g of primary packaging (tinplate cans), and 12.73 g of secondary packaging (cardboard).

All these materials are traced back to their origin (Figure 10.2). Canned mussel processing does not entail co-products, since mussel shells and mussel organic remains are waste streams sent to valorization plants for management. All waste flows and emissions are accounted for, as well as storage and waste transport.

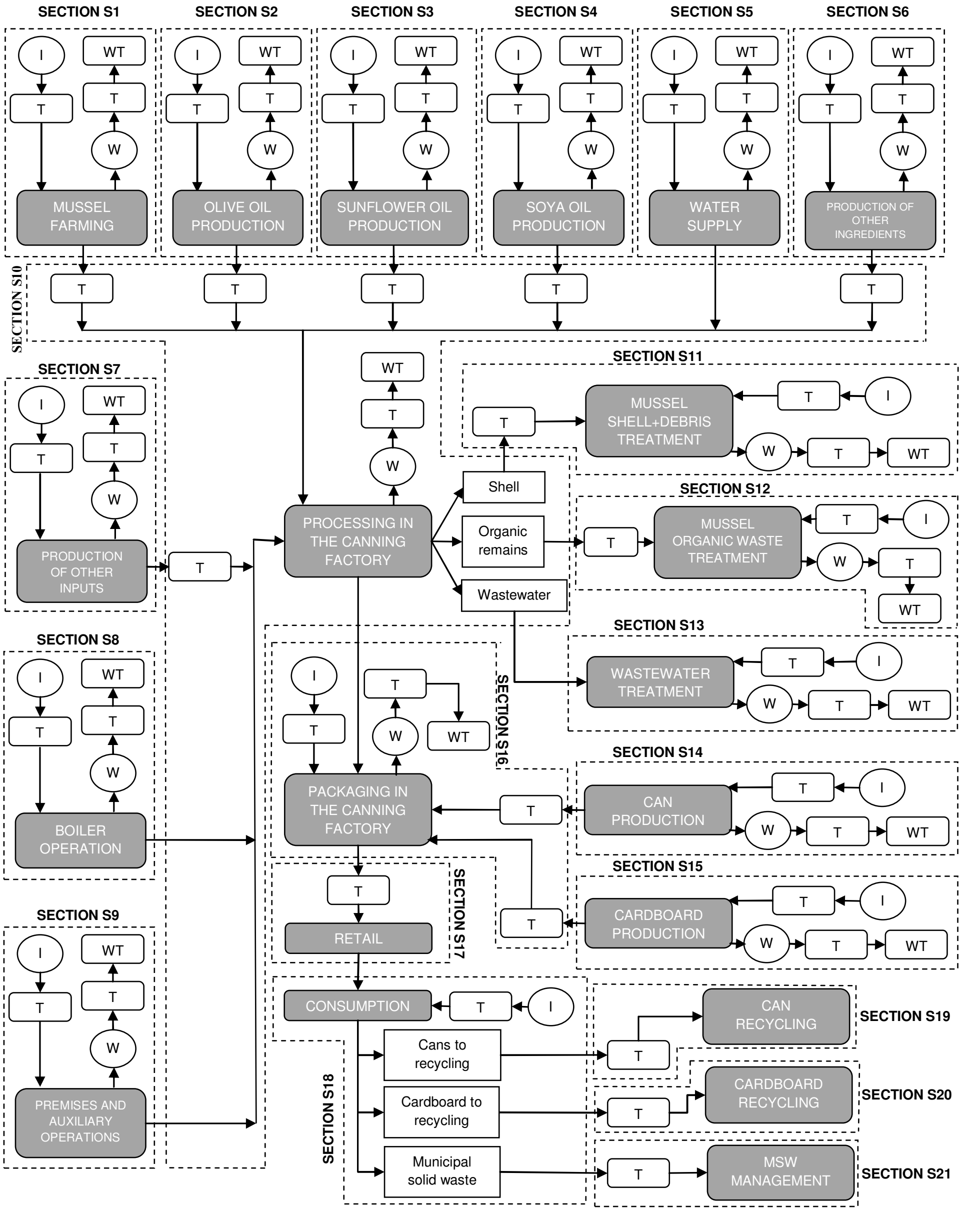

Figure 10.2. *Initial process map for the case study. Dotted lines represent sections. I = inputs; T = transport; W = waste; WT = waste treatment*

Regarding the consumer use stage, PAS 2050 excludes consumer transport. Canned mussels do not require cooking before consumption, refrigeration or freezing. Hence, the term consumption in Figure 10.2 only considers the production of the plastic bag used for shopping. Additionally, the use stage includes municipal solid waste management as well as the management of the packaging materials.

Checking boundaries and prioritization

This step determines the life cycle stages that are definitely included in the assessment. With this purpose, a preliminary assessment of the sources of GHG emissions is undertaken for all processes presented in the initial process map. According to PAS 2050, this initial estimate of GHG emissions is named "anticipated life cycle GHG emissions" and is calculated by means of secondary data or through a combination of primary and secondary data. The term secondary data relates to information obtained from sources other than direct measurement of the processes included in the life cycle of the product (BSI 2008).

Contributions for any source of GHG emissions resulting in ≤1% of the anticipated life cycle GHG emissions of the product (called "immaterial contributions") are excluded from the system boundaries provided that the total proportion of immaterial emission sources does not exceed 5% of the anticipated life cycle GHG emissions.

Table 10.1 presents the identification of immaterial contributions for the case study. As required by PAS 2050, the anticipated life cycle GHG emissions are estimated separately for the use phase. In order to simplify the presentation, the anticipated results are shown for sections and not for single processes, together with the data source used in each case. The values of global warming potentials (GWP100) to transform GHGs emission in kg of CO_2e are in accordance with the latest ones available from the IPCC (IPCC 2007). SimaPro 7 was the software used for the computation of the anticipated carbon footprint (Goedkoop et al. 2008).

As observed in Table 10.1, ecoinvent was chosen as the preferred database for secondary activity data (Frischknecht et al. 2007a). PAS 2050 gives preference to the use of data verified as being compliant with this PAS; however, a complete set of verified data is not yet available.

Table 10.1. *Anticipated life cycle GHG emissions of the FU*

Section assessed	kg CO_2e/FU	Main data source	Anticipated contribution (%)	Contribution type
		PREVIOUS TO CONSUMPTION		
S1) Mussel farming	$8.83\cdot10^{-2}$	Chapter 3	2.00	Material
S2) Olive oil production	$6.41\cdot10^{-3}$	Nicoletti et al. (2001)	0.14	Immaterial
S3) Sunflower oil production	$8.27\cdot10^{-3}$	Nicoletti et al. (2001)	0.19	Immaterial
S4) Soya oil production	$3.79\cdot10^{-3}$	ecoinvent database (Jungbluth et al. 2007)	0.09	Immaterial
S5) Tap water supply	$2.77\cdot10^{-5}$	ecoinvent database (Althaus et al. 2007)	0.00	Immaterial
S6) Production of other ingredients	$1.54\cdot10^{-4}$	ecoinvent database (Althaus et al. 2007)	0.00	Immaterial
S7) Production of other inputs	$1.53\cdot10^{-4}$	ecoinvent database (Althaus et al. 2007)	0.00	Immaterial
S8) Boiler operation	$5.68\cdot10^{-2}$	Chapter 4	1.28	Material
S9) Premises and auxiliary operations	$8.60\cdot10^{-4}$	Chapter 4	0.02	Immaterial
S10) Processing in the canning factory	$6.96\cdot10^{-2}$	Chapter 4	1.57	Material
S11) Mussel shell and debris treatment	$1.16\cdot10^{-1}$	Chapter 5	2.62	Material
S12) Mussel organic waste treatment	$-1.59\cdot10^{-3}$	Adapted from LCA food data base (Nielsen et al. 2003)	-0.04	Immaterial
S13) Wastewater treatment	$6.11\cdot10^{-3}$	Chapter 4	0.14	Immaterial
S14) Can production	3.95	ecoinvent database (Classen et al. 2007) BUWAL 250 database (Spriensma 2004)	89.25	Material
S15) Cardboard production	$9.62\cdot10^{-3}$	ecoinvent database (Hischier 2007)	0.22	Immaterial
S16) Packaging in the canning factory	$6.59\cdot10^{-2}$	Chapter 4	1.49	Material
S17) Retail	$4.50\cdot10^{-2}$	Transport: Chapter 4 Retail: LCA food data base (Nielsen et al. 2003)	1.02	Material
TOTAL PRE-CONSUMPTION	*4.42*		100.00	

Table 10.1. *Anticipated life cycle GHG emissions of the FU (cont.)*

Section assessed	kg CO_2e/FU	Main data source	Anticipated contribution (%)	Contribution type
		CONSUMPTION STAGE		
S18) Consumption (polyethylene bag production)	$7.88 \cdot 10^{-4}$	ecoinvent database (Hischier 2007)	2.16	Material
S19) Can recycling	-	Already involved in S14	-	-
S20) Cardboard recycling	-	Already involved in S15	-	-
S21) Municipal solid waste management	$3.58 \cdot 10^{-2}$	ecoinvent database (Doka 2007)	97.84	Material
TOTAL CONSUMPTION	*$3.66 \cdot 10^{-2}$*		100.00	
ANTICIPATED CARBON FOOTPRINT = 4.46 kg CO_2e/FU				

The choice of ecoinvent as the preferred database totally determines the result of the anticipated assessment. The use of the ecoinvent database for the tinplated sheet in section S14 (can production) is especially relevant. In this sense, if an older database such as BUWAL 250 (Spriensma 2004) is selected for can tinplate production, the contribution of S14 to the anticipated life cycle GHG emissions is lower (although this element is still the most important one) and, consequently, new material contributions arise. Thus, when using BUWAL 250, sunflower oil production results in a material contribution, accounting for an anticipated contribution of 1.11%. In this context of result variability due to database selection, the ecoinvent database was used when possible, as it is considered the most updated and complete available database. Nevertheless, section S3 (sunflower oil production) was included within the material contributions despite its low anticipated contribution percentage in Table 10.1. The inclusion of section S3 can be understood as a safety measure to avoid the omission of a potentially relevant contributor. Hence, concerning the stages previous to consumption, all material contributions accounted for 99.42% of the anticipated life cycle GHG emissions and, therefore, a factor of 1.006 is required to scale the final GHG emissions in order to take into account the excluded activities.

Regarding the use phase, sections S19 and S20 were omitted given that the recycling of packaging materials was already incorporated in the raw material content of cans (section S14) and cardboard (section S15). The rationale behind this decision is that the avoided emissions associated with the use of a percentage of metal scrap in cans and of paper-cardboard waste in carton are already implemented in sections S14 and S15, where a virtual closed loop recycling is assumed. In the use stage, material contributions accounted for 100% of the anticipated life cycle GHG emissions and, therefore, no scaling factor is required.

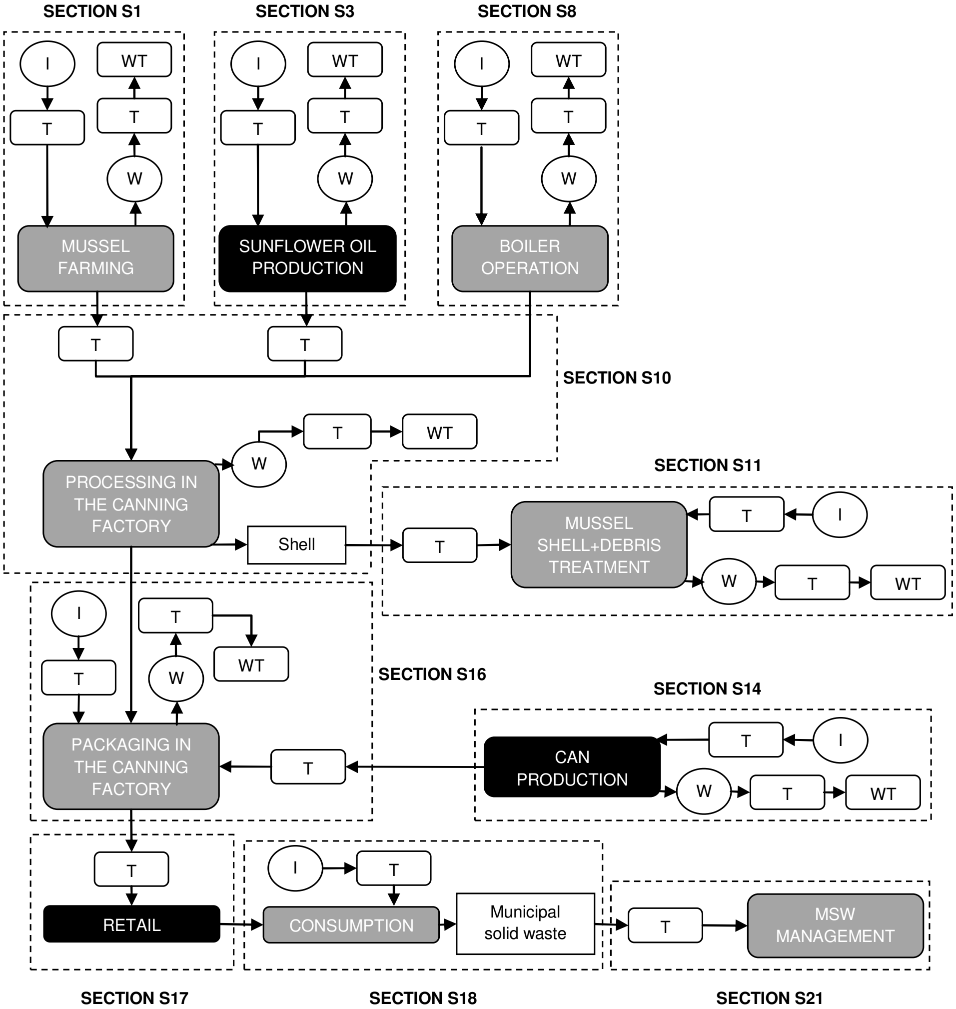

Figure 10.3. *Final process map after ruling out immaterial contributions. Dotted lines represent sections. Black boxes highlight the activities requiring primary activity data. I= inputs; T = transport; W = waste; WT = waste treatment*

The final process map is built by updating the initial one according to the conclusions drawn in Table 10.1. In the subsequent steps, the footprint calculation will just focus on the most significant contributors, which are those involved in the final process map (Figure 10.3). In Figure 10.3, the activities lacking in the use of primary activity data are filled in black to be distinguished from those which already avoided the use of secondary activity data.

Collecting data

Once known where to focus, more specific data are necessary. Thus, primary activity data are required for those activities filled in black in Figure 10.3, which in order of contribution are: can production, retail, and sunflower oil production. The rest of contributing activities already involved specific data for the Galician mussel sector in the calculation of the anticipated life cycle GHG emissions.

Can production

Cans are one of the main inputs to the target canning factory. The anticipated assessment revealed the need for primary activity data for the can section. In this sense, the can supplier checked the data set used in the anticipated study and, in consequence, four changes were deemed necessary (Comesaña 2009): the electricity demand for can production (1.30 Wh/can) and for easy-opening lid production (1.19 Wh/lid), as well as the amount of tinplate per can (18.00 g/can) and per easy-opening lid (10.35 g/lid). These changes led to a new value for the life cycle GHG emissions regarding the can section: 3.86 kg CO_2e/FU. This value means a reduction of 2.3% from the original figure.

Retail phase

The second activity needing more specific data is retail. In this case, pure primary data were not feasible because of the wide range of retailers. However, it is possible to get a more realistic estimate which takes into account the typical context of the product. Thus, consumers usually buy canned mussels in supermarkets. The corresponding electricity demand associated with space heating and cooling, water heating, lighting, process use, fans and small power has been taken from Elsayed et al. (2002), but assuming the Spanish profile for electricity production reported by the ecoinvent database (Dones et al. 2007). Consequently, the new value for the life cycle GHG emissions concerning section S17 is $1.26 \cdot 10^{-2}$ kg CO_2e/FU. This figure represents a decrease of 72% of the original estimate.

Sunflower oil production

Galician canning factories usually use sunflower oil produced in Spain. The Spanish sunflower oil production system comprises three main subsystems: (i) cultivation of sunflower seeds, (ii) production of crude sunflower oil, and (iii) refining.

Table 10.2. *Inventory for sunflower oil production in Spain (1 kg of sunflower oil)*

INPUTS					
From the environment					
1. Farming land	$7.69\cdot10^{-4}$	ha	2. Underground water	0.4615	m^3
From the technosphere					
Materials			**Other materials**		
1. Fresh water	3.0651	kg	1. Lubricating oil	0.0036	kg
2. Fertilizers			2. NaOH (50%)	0.0035	kg
Ammonium sulphate	0.3296	kg	3. H_2SO_4	0.0011	kg
Superphosphate	0.1490	kg	4. H_3PO_4	0.0019	kg
Potassium chloride	0.1880	kg	5. Citric acid	0.0450	g
3. Pesticides	0.0370	kg	6. Bleaching earth	0.0119	g
Active ingredients			7. Hexane	0.8769	g
Alachlor	9.0643	g	**Energy**		
Diazinon	0.1142	g	1. Electric energy	0.4015	kWh
Linuron	2.2831	g	**Transport**		
Metalaxyl	0.1142	g	1. Fertilizers	0.6680	t·km
4. Diesel	0.1210	kg	2. Pesticides	0.0371	t·km
5. Natural gas	0.5767	kWh	3. Sunflower seeds	0.0550	t·km
6. Steam	0.6577	kg	4. Crude sunflower oil	0.1450	t·km
OUTPUTS					
To the technosphere			**To the technosphere: waste to treatment**		
Products			1. Municipal solid waste	0.0144	kg
1. Sunflower oil	1.0000	kg	2. Hazardous waste	0.0145	g
Co-products[a]			3. Wastewater to treatment	3.0651	l
1. Sunflower heads and straw	0.1654	kg	**Emissions to the atmosphere**[b]		
2. Husks	1.1684	kg	1. CO_2	0.4754	kg
3. Vegetable raw fatty acids	0.0144	kg	2. N_2O	3.9603	g

[a] Economic allocation considered within each subsystem

[b] Only those emissions related to global warming

Primary activity data for the first two subsystems were provided by an international company located in southern Spain, while data related to the third subsystem came from another company, also in southern Spain, that refines more than 35,000 tonnes per year. Previous studies on sunflower oil (Cederberg 1998; Nicoletti et al. 2001; Shonfield & Dumelin 2005) also assisted in performing a comprehensive analysis of the corresponding life cycle GHG emissions. Table 10.2 shows an overall inventory of the relevant inputs and outputs involved in the production of sunflower oil in Spain.

Primary activity data for sunflower oil led to the following values –expressed per triple pack of round cans of mussels– for the life cycle GHG emissions for each subsystem: $2.02\cdot10^{-2}$ kg CO_2e/FU for the seed subsystem, $1.67\cdot10^{-3}$ kg CO_2e/FU for the crude oil subsystem, and $2.32\cdot10^{-3}$ kg CO_2e/FU for the refining subsystem. The new figure for the life cycle GHG emissions concerning the sunflower oil section is, therefore, $2.42\cdot10^{-2}$ kg CO_2e/FU. This represents three times the original value for this section.

Use profile

The Spanish average consumption of canned mussels is 0.21 kg per inhabitant and year (Sainz et al. 2008). As mentioned, no cooking, refrigeration or freezing is required. Consequently, production of shopping bags and waste management after consumption are the elements involved. In this case, waste management includes the management –as municipal solid waste– of all the plastic bags for shopping together with the percentage of the packaging waste that is not split for recycling.

A use profile consists of a description of the average behaviours of the end consumer (Carbon Trust et al. 2008). Using a volume-based allocation, 0.37 g of plastic shopping bag was estimated per FU. Shopping bags are normally reused as rubbish bags, so that amount of plastic is assumed to be disposed together with the municipal solid waste. Regarding the packaging waste, 63.6% of the cans and 62.2% of the cardboard are collected separately for recycling (Ecoacero 2009; IPE 2009), while the rest goes to general municipal solid waste management (i.e., incineration with energy recovery).

Calculating the carbon footprint

After having collected the relevant specific data, the final step is the definitive calculation of the product-level GHG emissions, that is, the carbon footprint for the triple pack of canned mussels as shown in Table 10.3.

Table 10.3. *Final calculation of the carbon footprint for the target good*

Section assessed	kg CO_2e/FU
PREVIOUS TO CONSUMPTION	
Mussel farming	$8.83\cdot10^{-2}$
Sunflower oil production	$2.42\cdot10^{-2}$
Boiler operation	$5.68\cdot10^{-2}$
Processing in the canning factory	$6.96\cdot10^{-2}$
Mussel shell and debris treatment	$1.16\cdot10^{-1}$
Can production	3.86
Packaging in the canning factory	$6.59\cdot10^{-2}$
Retail	$1.26\cdot10^{-2}$
TOTAL PRE-CONSUMPTION (scaling factor = 1.006)	*4.32*
CONSUMPTION STAGE	
Consumption (bag production)	$7.88\cdot10^{-4}$
Municipal solid waste management	$3.58\cdot10^{-2}$
TOTAL CONSUMPTION (scaling factor = 1.000)	$3.66\cdot10^{-2}$
FINAL CARBON FOOTPRINT = 4.35 kg CO_2e/FU	

The use of CF for canned mussels not only gives a number (4.35 kg CO_2e/FU) but it also allows the different stakeholders to prioritize opportunities to reduce the GHG emissions associated with the product chain. In this particular case, efforts should focus on primary packaging (can production).

10.4. Discussion

CF has been put into practice for a canned mussel product using PAS 2050. It led to a final result of 4.35 kg CO_2e for one triple pack of round cans of canned mussels. However, an important characteristic of carbon footprints is the fact that they constitute a representative figure where natural variability is implicit. Additionally, there are also some methodological aspects that are source of technical uncertainty and question the potential of using a number to truly represent the contribution of a product to the global GHG emissions.

The anticipated value for the carbon footprint was 4.46 kg CO_2e/FU. This means an increase of 2.38% respect to the final value, which is not excessive, mainly due to the use of a combination of primary and secondary data instead of only secondary data for the anticipated assessment. Note that this figure (+2.38%) does not constitute a measure of uncertainty, but it is used as an indicator on the differences entailed by the changes in data for the final assessment and by the use of a scaling factor.

For the specific case study described in this chapter, there is a PAS 2050 decision which becomes crucial: the exclusion of the GHG emissions arising from the production of capital goods used in the life cycle of the product. Although draft versions of PAS 2050 included capital goods emissions (Sinden 2009), the current version excludes them and leaves the analysis of inclusion for future revisions of the specification (BSI 2008). The omission of capital goods can result in the removal of material contributions to the GHG emissions for some product categories; which is especially true for agricultural products (Frischknecht et al. 2007b) and also for seafood from extensive aquaculture (Chapter 3). On the one hand, since the assessed canned mussel product is based on mussels cultured in rafts (extensive aquaculture practice), the inclusion of the GHG emissions arising from capital goods would provide mussel processors with a more representative value for the carbon footprint of the product. Even though mussel farming was already found as one of the main activities contributing to the life cycle GHG emissions, the inclusion of capital goods emissions would entail a much greater contribution of mussel cultivation to the carbon footprint of the canned mussel product, indisputably becoming the main contributor to GHG emissions. On the other hand, agricultural processes included in the process map (vegetable oils) would also play a more relevant role and could even turn immaterial contributions into material. It is concluded that future versions of PAS 2050 should include capital goods (even based on secondary data) for the calculation of product carbon footprints.

Besides being a sole figure, CF is also a single indicator. However, products bring about more environmental consequences than just global warming. Among the most common impact categories considered for seafood research are global warming, abiotic depletion, acidification, eutrophication, photochemical oxidant formation and ozone layer depletion (Pelletier et al. 2007). The risk of an uncontrolled use of CF is to underestimate the need for the rest of impact indicators which are essential to get a comprehensive understanding of the environmental performance of a product.

Despite these drawbacks, CF should be used as a catalyst for life cycle thinking and LCA (Weidema et al. 2008). In the case study of canned mussels, CF was able to provide chain transparency and accountability for the seafood industry, which is currently an acknowledged need (Iles 2007; Ayer et al. 2009). Thus, a responsible use of CF would drive the implementation of life cycle thinking into companies and could encourage a more thorough framework for the environmental assessment of products. Policy makers should be involved in the promotion of a responsible use of CF schemes.

The use of CF as a tool to support decision making in organizations would benefit from the previous application of LCA. A preliminary LCA of a product could highlight the role of different impact categories so that, if global warming results relevant, a subsequent CF study should be undertaken. LCA and CF as facilitative instruments are also useful for benchmarking. Nevertheless, when benchmarking is pursued and data are available for a number of similar facilities, the preferred approach should be the combined application of LCA and DEA as developed in chapters 8 and 9. In this respect, while the single use of CF would just provide a benchmark for measuring and communicating emission reductions, the use of an LCA+DEA method would provide both companies and policy makers with current and target values to be used as operational and environmental benchmarks.

The case study discussed in this chapter also showed the potential of CF for marketing purposes. In the case of the Galician mussel sector, regional actors seek the reinforcement of their market position versus foreign mussel products with an increasing presence in international markets. This reinforcement should be gained through the competitive advantages of product differentiation. Carbon footprint communication for mussel products would constitute a measure addressed to achieve differentiation. This chapter could be used as a support document for regional mussel processors to implement a CF scheme and to anticipate future regulations and requirements on global warming.

Finally, PAS 2050 is the reference document recommended for carrying out CF studies. A key strength of this specification is its orientation towards products rather than towards organizations, unlike other well-known CF methods such as Bilan Carbone^{TM} (ADEME 2007). This feature, together with the consistency of the method, results in a wider acceptance of PAS 2050, rather than other proposals. While the uncontrolled proliferation of CF standards would result counter-productive, fortunately the current trend is to take PAS 2050 specifications as the master guidelines that conduct the product carbon footprint assessment. In this sense, the development of the future ISO 14067 standard for quantification and communication of product carbon footprints draws on PAS 2050.

10.5. Conclusions and perspectives

In this chapter, CF was proved to be a useful tool for the internal assessment of life cycle GHG emissions. Moreover, it led to the identification of opportunities to reduce these emissions. In this sense, CF arises as a potential support for decision making in companies, even though it provides a limited view of the environmental performance of a product since global warming is the only impact category assessed. Despite this drawback, the greatest strength of CF lies in the use of a life-cycle approach and in its popularity. Therefore, it is possible to think of product policies that promote the implementation of CF schemes. These policies should not be understood as definitive but as a provisional vehicle to a more comprehensive policy framework for the environmental assessment of products based on their life cycle.

In the short term, companies are expected to incorporate CF schemes for their products as a strategic measure for both marketing and decision making. This practice will be performed by following a well-defined method which guarantees traceability, comparability and a proper communication. PAS 2050 seems to be ahead in this field. In the long run, policy makers should pursue the commitment of companies to undertake CF schemes as facilitative instruments within their activity. Undoubtedly, the path is open for CF.

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SECTION V.

GENERAL CONCLUSIONS

Chapter 11

General conclusions

The path towards sustainability in the food sector demands the modification of the current operational and environmental patterns. In this sense, it is necessary to pursue reductions in the consumption levels for materials and energy, as well as the mitigation of the corresponding environmental impacts.

Within this context, LCA arises as a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

This doctoral thesis contributes to the gradual establishment of LCA to evaluate seafood production systems by widening the range of species studied and developing further potentials in the application of LCA such as the combined use of DEA and LCA, or the implementation of CF schemes.

The application of LCA to the Galician mussel (*Mytilus galloprovincialis*) and turbot (*Scophthalmus maximus*) aquaculture sectors proved the suitability of LCA to assess the environmental performance of these key economic sectors. In this respect, the use of LCA provided chain transparency and accountability all along the trade chain for mussels and turbot.

Mussels are the leading product of the Galician aquaculture. This bivalve mollusc is cultured in rafts according to an extensive aquaculture practice. Mussel culture gives rise to a complex sector involving not only farming but also a variety of activities that are performed by different economic actors depending on the processing alternative selected for mussel transformation. The novel LCA of the Galician mussel sector led to these key messages and conclusions:

- ➢ Average models for rafts and auxiliary boats for mussel culture were defined on the basis of real *in situ* data from a set of vessels that operate in the main production areas.

- Detailed inventories are now available for mussel farming, mussel processing (in canning factories, cooking-freezing plants and partial canning factories), mussel consumption in households (as fresh, canned and frozen mussels), and mussel waste valorization (valorization of mussel shells to produce calcium carbonate, and valorization of mussel organic remains to produce pâté).
- The dispatch centres sub-sector was found to be the most contributing to the potential environmental impacts when capturing the real market scenario for mussels. On the contrary, the cooking plants and canning factories sub-sectors entailed lower impact contributions when compared to the culture and dispatch centres sub-sectors.
- Mussel shell valorization and mussel organic waste management contribute to the potential environmental impacts to a lesser extent than mussel culture, mussel purification and, generally, mussel transformation in canning factories.
- Minimization of electricity use in dispatch centres is of paramount importance.
- Improvement actions for mussel culture should be focused on the optimization of the diesel demand for vessel operation as well as on the minimization of the energy and iron demand for capital goods.
- Fresh mussels were the mussel product with the potentially least favourable environmental profile when compared to canned and frozen mussels on the basis of a same protein supply. This higher potential environmental impact is closely linked to mussel purification within dispatch centres.

Regarding the Galician intensive aquaculture, turbot is the main species. Turbot farming in Galicia accounts for around 90% of the national turbot production. As an intensive aquaculture practice, turbot farming demands external feeding. General conclusions from the application of LCA to aquafeed production and turbot aquaculture include:

- Inventories for the production of both marine and continental aquafeed were provided, together with thorough inventories for turbot farming (hatching and nursing, growing, ongrowing) and consumption.
- Recommendations for aquafeed manufacturers are centred on raw material production. New raw materials and/or different ingredient ratios for aquafeed should be assessed.

- Electricity use in hatching facilities is the main hot spot within turbot aquaculture, ahead of aquafeed and diesel use in ongrowing plants. Hence, turbot farmers should pursue the minimization of the electricity demand in these facilities.
- A rough comparison between intensive and extensive aquaculture sectors was established by assuming turbot and mussels as their respective representatives. Extensive aquaculture showed a potentially worse environmental profile, mainly due to the unsustainable electricity use in mussel dispatch centres and to the role played by capital goods for mussel culture.

In addition to the application of LCA to mussel and turbot aquaculture sectors, further potentials in the use of LCA were developed, specifically the combined application of LCA and DEA, and the assessment of carbon footprints.

DEA is a performance measurement methodology used to empirically quantify the comparative productive efficiency of multiple similar entities. This tool featured appealing potentials when jointly applied with LCA. The key messages on the application of LCA+DEA methodology are:

- An LCA+DEA approach joins the strengths and minimizes the weaknesses attributable to both methodologies so that a synergistic effect is achieved while maintaining a quantitative character.
- The strength of LCA+DEA methodology comes from its quantitative character since it is able to set targets and quantify potential improvements.
- The use of an LCA+DEA approach avoids the use of average inventories when assessing a high number of similar facilities. Consequently, undesirable standard deviations are prevented.
- LCA+DEA methods are not limited to environmental impacts but add an economic dimension to the sustainability assessment.
- The five-step LCA+DEA method developed in this doctoral thesis arises as a tool for eco-efficiency verification. This approach quantifies the environmental consequences of operational inefficiencies.
- The application of the five-step LCA+DEA method to Galician mussel cultivation sites proved the direct link between operational efficiency and environmental impacts. Operationally inefficient rafts were identified and

significant input reductions were determined. These operational targets resulted in considerable reductions in potential environmental impacts.

- The three-step LCA+DEA method presented in this dissertation enables the determination of the environmental impact efficiency for a given set of DMUs.
- The application of the three-step LCA+DEA approach to mussel cultivation sites proved the ability of this approach to simultaneously compute target input consumption levels and target environmental impacts for each raft.
- Both the three- and the five-step LCA+DEA approaches are rather general and can be applied in other LCA studies. The main requirement is to have data for a sample of DMUs large enough to guarantee discriminant power.

Finally, CF involves the estimation of the carbon footprint of a product. The term product carbon footprint refers to the GHG emissions of a product across its life cycle, from raw materials through production, distribution, consumer use and disposal/recycling. The application of the PAS 2050 guidelines for the CF of a common canned mussel product led to the following general conclusions:

- CF is a useful tool for the internal assessment of life cycle GHG emissions. The implementation of a CF scheme enables the identification of opportunities to reduce GHG emissions. Therefore, CF arises as a potential support for decision making in companies.
- CF provides a limited view of the environmental performance of a product since global warming is the only impact category assessed. Despite this relevant drawback, the greatest strength of CF lies in the use of a life-cycle approach and in its increasing popularity.
- Product policies that promote the implementation of CF schemes are possible. These policies should not be understood as definitive but as a provisional vehicle to a more comprehensive policy framework for the environmental assessment of products based on their life cycle.
- Companies are expected to incorporate CF schemes for their products as a strategic measure for both marketing and decision making. This practice will be performed by following a well-defined method which guarantees traceability, comparability and a proper communication. PAS 2050 seems to be ahead in this field.

ADDITIONAL CONTENTS

Annex I

Resumen

El sector pesquero gallego es el más importante de España. Su facturación económica superó los mil millones de euros en 2007, aportando más del 10% del PIB gallego.

En el marco del sector pesquero, existe una actividad en la que Galicia se presenta como líder a nivel nacional. Se trata de la acuicultura gallega, que puede ser entendida como un sector en sí mismo y que proporciona más del 80% de la producción acuícola española.

Tradicionalmente, se distinguen dos grandes tipos de acuicultura. Por una parte, se encuentra la acuicultura extensiva, que consiste en un cultivo dirigido principalmente a moluscos y que no requiere de alimentación artificial. Por otra parte, la acuicultura intensiva se presenta como un método de cultivo de peces marinos o continentales que exige alimentación externa.

En esta tesis doctoral, se evalúa ambientalmente el sector acuícola en base a dos especies de referencia en la acuicultura extensiva e intensiva tanto gallega como española. Se trata del sector mejillonero gallego como representante de la acuicultura extensiva, y el sector acuícola gallego del rodaballo como estandarte de la acuicultura intensiva. La herramienta empleada para la evaluación ambiental de los sectores acuícolas de mejillón y rodaballo es el Análisis del Ciclo de Vida (ACV por sus siglas en castellano, o LCA por sus siglas en inglés).

El camino hacia el desarrollo sostenible en el sector alimentario requiere la modificación de los patrones operacionales y ambientales actuales. A este respecto, se precisan importantes reducciones en los niveles de consumo de materia y energía, e igualmente se necesita la mitigación del impacto ambiental. La sostenibilidad ambiental consiste en la capacidad de mantener las características de valor del medio físico. Las herramientas de gestión ambiental se desarrollaron para ayudar a las compañías a la hora de controlar, mejorar y gestionar adecuadamente su desempeño ambiental, así como para colaborar en la integración de los aspectos ambientales, económicos y sociales. La gran variedad de herramientas ambientales hace posible la implementación, en el seno del entramado empresarial, de estrategias de ecoeficiencia, del enfoque de ciclo de vida y de sistemas de gestión ambiental.

En concreto, el ACV es una técnica para la evaluación de los impactos ambientales potenciales asociados a un producto (bien o servicio). Para ello, se recopila un inventario de las principales entradas y salidas para un determinado sistema de producto, y se evalúan los impactos ambientales potenciales ligados a tales entradas y salidas. El ACV adopta una perspectiva de la cuna a la tumba, analizando los impactos de un producto a lo largo de todo su ciclo de vida, es decir, desde la adquisición de las materias primas (la cuna), pasando por su producción y uso, hasta su disposición final (la tumba).

Uno de los sectores donde el ACV se encuentra ampliamente implantado es el sector agroalimentario. Sin embargo, mientras el ACV en agricultura se halla bastante bien establecido, el uso de esta herramienta para la evaluación de sistemas productivos de alimentos marinos constituye un fenómeno más reciente.

Por lo tanto, esta tesis contribuye a ampliar el número de especies acuáticas estudiadas bajo un enfoque de ACV mediante la evaluación ambiental de los sectores acuícolas gallegos del mejillón (*Mytilus galloprovincialis*) y del rodaballo (*Scophthalmus maximus*), identificando sus puntos ambientalmente críticos y proponiendo potenciales de mejora. Más allá de la aplicación de la metodología de ACV al sector acuícola, esta tesis también desarrolla nuevas tendencias en la utilización del ACV, concretamente profundiza en los potenciales de la aplicación conjunta de ACV y Análisis por Envoltura de Datos (DEA por sus siglas inglesas), y en la implementación de estrategias de evaluación de huella de carbono (CF por sus siglas en inglés).

La tesis se divide en once capítulos recogidos en cinco secciones. La primera sección abarca los dos primeros capítulos, en los que se contextualiza el estudio mediante la introducción del sector acuícola y de las principales herramientas de gestión utilizadas (ACV, DEA y CF).

La segunda sección se centra en la aplicación del ACV al sector mejillonero gallego. No sólo se incluye el análisis del cultivo de mejillón (Capítulo 3) sino que también se evalúan su procesado y consumo (Capítulo 4), y el tratamiento de residuos específicos del sector mejillonero (Capítulo 5). Consecuentemente, se

llega a una completa evaluación ambiental gracias al ACV de los tres productos clásicos de mejillón: mejillón fresco, mejillón en conserva y mejillón congelado.

La tercera sección comprende la evaluación mediante ACV del sector acuícola del rodaballo en Galicia. Primeramente, se lleva a cabo un estudio de ACV para la producción de piensos de acuicultura (Capítulo 6) ya que se sabe que estos piensos constituyen un elemento clave en el comportamiento ambiental de las plantas acuícolas. Tras ello, el Capítulo 7 integra el ACV de piensos marinos en el caso de estudio del cultivo y consumo de rodaballo.

La cuarta sección se reserva al desarrollo y aplicación de metodologías íntimamente ligadas al ACV. Así, se plantea el uso conjunto de ACV y DEA, mostrándose además su aplicación en el caso de la miticultura (es decir, en el cultivo de mejillón) bajo dos perspectivas diferentes: eficiencia operacional (Capítulo 8) y eficiencia ambiental (Capítulo 9). Por otra parte, el Capítulo 10 ejemplifica el cálculo de la huella de carbono utilizando para ello un producto típico de mejillón en conserva y las pautas propuestas por la especificación PAS 2050, que se está consolidando como metodología de referencia para la evaluación de huellas de carbono.

La quinta sección se compone de un único capítulo (Capítulo 11) donde se recogen las conclusiones generales derivadas de esta tesis doctoral.

Los mejillones son el producto estrella de la acuicultura gallega. Este molusco bivalvo se cultiva en bateas siguiendo un procedimiento acuícola extensivo que requiere un mínimo control por parte del cultivador y que no necesita aporte externo de nutrientes ni participación durante el proceso reproductivo. Las bateas gallegas producen el 98% de los mejillones cultivados en España. El Capítulo 3 recoge el primer ACV llevado a cabo para la fase de cultivo de mejillón. Con este fin, se estudiaron las principales áreas productivas gallegas. Los datos de inventario se obtuvieron de entrevistas y encuestas realizadas para un conjunto de embarcaciones que conlleva la producción de más de siete mil toneladas de mejillón. La caracterización ambiental incluyó las siguientes categorías de impacto: agotamiento de los recursos abióticos, calentamiento global, agotamiento de la capa de ozono, toxicidad humana, ecotoxicidad (marina, de agua dulce y terrestre), formación de oxidantes fotoquímicos, acidificación y eutrofización. Los resultados de dicha caracterización revelaron la importancia de considerar no sólo los aspectos operacionales, sino también los bienes capitales

(instalaciones y equipos). El consumo de diesel para la operación de la embarcación resultó ser el principal motivo de los impactos ambientales potenciales, junto con el uso de energía y hierro para los bienes capitales. No obstante, se necesitaría un estudio más pormenorizado de los bienes capitales.

El cultivo de mejillón da lugar a un complejo sectorial que no sólo incluye las actividades acuícolas sino también un entramado de actividades ligadas al procesado del mejillón. A este respecto, además del subsector de cultivo de mejillón, se pueden distinguir tres subsectores principales en función de los centros donde tiene lugar la transformación del mejillón: (i) subsector de las estaciones depuradoras de moluscos, (ii) subsector de las empresas conserveras, y (iii) sub-sector de los cocederos de mejillón y empresas conserveras parciales (es decir, conserveras que reciben la vianda de mejillón ya cocida). El Capítulo 4 incluye la evaluación ambiental mediante ACV del procesado y consumo de mejillón. La elaboración y uso de inventarios exhaustivos condujo a la caracterización ambiental del sector mejillonero en términos de la contribución de cada uno de los subsectores a los impactos ambientales potenciales. En este sentido, el subsector de las estaciones depuradoras de moluscos (responsables del suministro de mejillón fresco) contó con las mayores contribuciones, claramente por delante del subsector de cultivo. Los subsectores de las empresas conserveras y de los cocederos de mejillón presentaron unas contribuciones mucho menores. Los potenciales de mejora propuestos destacaron la necesidad de minimizar el consumo de energía eléctrica en las estaciones depuradoras de moluscos. Por otra parte, se llevó a cabo un ACV comparativo a fin de contrastar el perfil ambiental de los tres principales productos de mejillón. Así, este análisis concluyó que los mejillones frescos conllevan el perfil ambiental más desfavorable cuando son comparados con los mejillones en conserva y con los mejillones congelados.

El procesado del mejillón da lugar a una serie de residuos específicos de la industria mejillonera. Entre estos residuos, destacan la concha de mejillón y los restos orgánicos de mejillón. El Capítulo 5 trata la gestión tanto de la concha como de los restos orgánicos de mejillón desde un enfoque de ACV. Por una parte, se procedió a la caracterización ambiental de la valorización de la concha de mejillón para producir carbonato cálcico. Consecuentemente, el consumo de propano y energía eléctrica, la gestión del lodo y las cenizas, el transporte y las emisiones atmosféricas fueron identificados como los puntos ambientalmente críticos donde deberían centrarse los potenciales de mejora. En este sentido, se realizó la evaluación ambiental de un escenario futuro para estimar las consecuencias ambientales potenciales en el caso de adoptar tres medidas concretas: uso de glicerina en vez de propano, consideración de las cenizas de proceso como un producto y no como un residuo, y valorización del lodo. El ACV reflejó que dicho escenario futuro podría suponer un peor desempeño ambiental con respecto a la situación actual, a menos que solamente se adoptasen las medidas concernientes a las cenizas y al lodo. Además, se evaluó ambientalmente la conveniencia de la valorización de la concha de mejillón en comparación con otras alternativas para la gestión de residuos (vertedero e incineración). La incineración resultó ser la opción menos favorecida, mientras que decantarse por el envío a vertedero podría implicar un mejor desempeño ambiental pero supondría problemas de ocupación de terreno y desventajas socioeconómicas. Por otra parte, también se caracterizó ambientalmente la valorización de los restos orgánicos de mejillón para producir paté. A raíz de esta caracterización, se llegó a la recomendación de mejoras centradas en la proporción de los ingredientes (minimización del consumo de aceite, leche en polvo, aromas y especias) así como en la optimización logística (transporte del paté) y energética (energía calorífica). La implementación de los sistemas de valorización de la concha y los restos orgánicos de mejillón dentro del caso de estudio general del mejillón reveló que estos sistemas de gestión sí que contribuyen a los impactos ambientales potenciales, pero con unos valores de caracterización inferiores a los correspondientes al cultivo y procesado de mejillón.

Aunque la acuicultura extensiva del mejillón domina la acuicultura gallega, la acuicultura intensiva de peces marinos también goza de un papel relevante, con niveles de producción cercanos a las seis mil toneladas anuales. La acuicultura del rodaballo es responsable del 95% de la producción y facturación vinculadas a la acuicultura intensiva gallega. Así, el cultivo de rodaballo en Galicia supone más del 25% de la facturación acuícola autonómica, y proporciona alrededor del 90% de la producción española de rodaballo de acuicultura. Los capítulos 6 y 7 abordan el ACV de la acuicultura intensiva del rodaballo. Desde un punto de vista ambiental, se sabe que los piensos de uso acuícola constituyen un aspecto clave en cuanto a su contribución a los impactos ambientales potenciales. Por ello, el Capítulo 6 se basa en llevar a cabo un ACV para la producción de piensos destinados a acuicultura, abarcando tanto piensos para acuicultura intensiva marina como piensos para acuicultura intensiva continental. La formulación de los piensos resultó ser el foco donde centrar las acciones de mejora. Por lo tanto, los productores de piensos deberían evaluar el empleo de nuevos ingredientes o la utilización de diferentes proporciones en su formulación. El desarrollo de un ACV detallado para los piensos acuícolas marinos permitió su implementación en el seno del ACV para el cultivo y consumo de rodaballo, que fue el objeto de estudio del Capítulo 7. La caracterización ambiental de la acuicultura gallega de rodaballo condujo a la identificación del consumo eléctrico en los criaderos de rodaballo como el principal punto crítico, por delante del consumo de piensos y diesel en las plantas de engorde. Además, se estableció una comparación aproximada entre acuicultura intensiva y acuicultura extensiva tomando como referentes el cultivo de rodaballo y mejillón, respectivamente; y adoptando como unidad funcional un mismo aporte proteínico. Consecuentemente, de manera general, el sector acuícola extensivo (mejillón) mostró un peor comportamiento ambiental que el sector acuícola intensivo (rodaballo).

La aplicación del ACV a los sectores acuícolas del mejillón y rodaballo en Galicia demostró la capacidad de esta herramienta para proporcionar transparencia y trazabilidad a lo largo de toda la cadena comercial de mejillones y rodaballo. No obstante, esta tesis doctoral no sólo aplica la metodología del ACV, sino que también desarrolla y discute nuevas tendencias en el empleo del ACV, como son la aplicación conjunta de ACV y DEA, y la evaluación de huellas de carbono (CF).

El DEA es una metodología empleada para cuantificar la eficiencia productiva de múltiples entidades similares. Para llevar a cabo un DEA, deben conocerse los datos de las principales entradas y salidas de cada una de las entidades. A partir de estos datos, esta herramienta formula y resuelve un modelo de optimización que facilita el benchmarking del desempeño operacional de cada entidad evaluada. El DEA discrimina los puntos operacionalmente ineficientes y propone mejoras tecnológicamente plausibles bajo la perspectiva de una actuación operacional eficiente. Por otra parte, los impactos ambientales dependen de la eficiencia con la que se ejecutan las operaciones. En el caso de disponer de los datos de inventario del ciclo de vida para múltiples instalaciones similares, entonces podría realizarse el benchmarking del desempeño operacional de cada instalación mediante DEA. Los capítulos 8 y 9 desarrollan el uso sinérgico de ACV y DEA como un enfoque metodológico que liga la eficiencia operacional y los impactos ambientales. En particular, el Capítulo 8 propone el método ACV+DEA de cinco pasos como una metodología que aglutina el benchmarking operacional, la verificación de ecoeficiencia y la evaluación de los impactos ambientales potenciales. Este método se aplicó a una amplia muestra de bateas de mejillón a fin de demostrar su aplicabilidad y utilidad. Consecuentemente, se detectaron las bateas operacionalmente ineficientes y se propusieron sus correspondientes valores objetivo a nivel operacional. El método ACV+DEA de cinco pasos demostró la dependencia de los impactos ambientales con respecto al desempeño operacional, y favoreció la cuantificación de los beneficios potenciales dentro del marco conceptual de la ecoeficiencia.

La aplicación conjunta ACV+DEA permite conjugar las fortalezas y minimizar las debilidades de ambas metodologías de manera que se logra un efecto sinérgico a la vez que se mantiene el carácter cuantitativo. Los métodos ACV+DEA presentan las ventajas de evitar el uso de inventarios promedio (eludiendo, por lo tanto, las desviaciones estándar asociadas) y de añadir una dimensión económica (operacional) al análisis ambiental. Estas ventajas se consiguen mediante la aplicación del método ACV+DEA de cinco pasos, pero también se obtienen al aplicar el método ACV+DEA de tres pasos desarrollado en el Capítulo 9. Este segundo enfoque de tres pasos permite determinar la eficiencia ambiental así como estimar directamente los impactos ambientales potenciales objetivo. Su aplicabilidad fue también demostrada en el caso de las bateas de mejillón. Así, se identificaron las bateas operacional y ambientalmente ineficientes, y se propusieron directamente las mejoras plausibles tanto en los consumos operacionales como en los impactos ambientales potenciales. Los dos métodos ACV+DEA planteados pueden considerarse de aplicación general para cualquier estudio de ACV siempre y cuando se disponga de datos para múltiples entidades similares.

Por último, la creciente concienciación acerca del cambio climático como un problema de carácter global ha llevado a las grandes empresas a solicitar un procedimiento estandarizado para la medición y comunicación de las emisiones de efecto invernadero ligadas a los productos destinados al consumidor. En este contexto, el CF se ha erigido como la herramienta de aplicación para la evaluación de la huella de carbono de productos. Como se discute en el Capítulo 10, esta herramienta resulta de utilidad tanto para las compañías a lo largo de la cadena del producto como para los legisladores.

El CF implica la estimación de la cantidad global de las emisiones de efecto invernadero vinculadas a un producto (bien o servicio) a lo largo de su cadena de abastecimiento, incluyendo su uso y disposición final. Por lo tanto, el término huella de carbono se refiere a las emisiones de efecto invernadero de un producto a través de su ciclo de vida, abarcando tanto las materias primas como la producción, distribución, uso por parte del consumidor y la disposición final/reciclaje. Como gases de efecto invernadero se incluyen el dióxido de carbono, el metano y el óxido nitroso, junto con familias de gases que comprenden los hidrofluorocarbonos y los perfluorocarbonos. No obstante, el CF no debería entenderse como un simple ACV restringido a la categoría de impacto del calentamiento global dado que su reciente auge está promoviendo la construcción de un marco metodológico sólido que garantice el poder de comparación y comunicación. A este respecto, la especificación PAS 2050 proporciona un método de aplicación general para el CF de un producto cuya aceptación se prevé amplia. El Capítulo 10 utiliza el caso de estudio del mejillón para ejemplificar y discutir la implementación del CF para un producto típico de mejillón en conserva de acuerdo con las pautas definidas por la especificación PAS 2050. A lo largo de la evaluación de la correspondiente huella de carbono, se identificaron las fortalezas y debilidades principales de este enfoque, proporcionando a la vez un punto de partida para que los procesadores de mejillón y los legisladores se beneficien de las ventajas que conlleva la utilización responsable del CF. Así, el CF demostró ser una herramienta útil para la evaluación interna de las emisiones de efecto invernadero a lo largo del ciclo de vida del producto. Además, su aplicación condujo a la identificación de puntos susceptibles de mejora. Por lo tanto, el CF se presenta como un interesante apoyo para la toma de decisiones en el seno de las compañías. Sin embargo, es cierto que el CF aporta una visión limitada del desempeño ambiental de un producto debido a que sólo se evalúa una única categoría de impacto (el calentamiento global). Mientras que esto constituye un inconveniente importante, la gran fortaleza del CF radica en el uso de un enfoque de ciclo de vida y en su creciente popularidad. Esto hace posible la elaboración de políticas que promuevan la implementación de estrategias de CF y sirvan así de vehículo provisional hacia un marco político integral para la evaluación ambiental de productos en base a su ciclo de vida.

Annex II

Resumo

O sector pesqueiro galego é o máis importante de España. A súa facturación económica superou os mil millóns de euros no 2007, aportando máis do 10% do PIB galego.

No marco do sector pesqueiro, existe unha actividade na que Galicia preséntase como líder a nivel nacional. Trátase da acuicultura galega, que pode ser entendida como un sector en si mesmo e que proporciona máis do 80% da produción acuícola española.

Tradicionalmente distínguense dous grandes tipos de acuicultura. Por unha parte, atópase a acuicultura extensiva, que consiste nun cultivo dirixido principalmente a moluscos e que non require de alimentación artificial. Por outra parte, a acuicultura intensiva preséntase como un método de cultivo de peces mariños ou continentais que esixe alimentación externa.

Nesta tese de doutoramento, avalíase ambientalmente o sector acuícola en base a dúas especies de referencia na acuicultura extensiva e intensiva tanto galega como española. Trátase do sector mexilloneiro galego como representante da acuicultura extensiva, e do sector acuícola galego do rodaballo como estandarte da acuicultura intensiva. A ferramenta empregada para a avaliación ambiental dos sectores acuícolas de mexillón e rodaballo é a Análise do Ciclo de Vida (ACV polas súas siglas en galego/castelán, ou LCA polas súas siglas en inglés).

O sendeiro cara o desenvolvemento sostible no sector alimentario require a modificación dos patróns operacionais e ambientais actuais. Neste respecto, precísanse importantes reducións nos niveis de consumo de materia e enerxía, e asemade necesítase a mitigación do impacto ambiental. A sostibilidade ambiental consiste na capacidade de mante-las características de valor do medio físico. As ferramentas de xestión ambiental desenvolvéronse para axudar ás compañías á hora de controlar, mellorar e xestionar axeitadamente o seu desempeño ambiental, así como para colaborar na integración dos aspectos ambientais, económicos e sociais. A gran variedade de ferramentas ambientais fai posible a implementación, no seo do entramado empresarial, de estratexias de ecoeficiencia, do enfoque de ciclo de vida e de sistemas de xestión ambiental.

En concreto, a ACV é unha técnica para a avaliación dos impactos ambientais potenciais asociados a un produto (ben ou servizo). Para elo, recompílase un inventario das principais entradas e saídas para un determinado sistema de produto, e avalíanse os impactos ambientais potenciais ligados a esas entradas e saídas. A ACV adopta unha perspectiva do berce ata a tumba, analizando os impactos dun produto ó longo de todo o seu ciclo de vida, é dicir, dende a adquisición das materias primas (o berce), pasando pola súa produción e uso, ata a súa disposición final (a tumba).

Un dos sectores onde a ACV atópase amplamente implantada é o sector agroalimentario. Sen embargo, mentres a ACV en agricultura áchase bastante ben establecida, a utilización desta ferramenta para a avaliación de sistemas produtivos de alimentos mariños constitúe un fenómeno máis recente.

Polo tanto, esta tese contribúe a amplia-lo número de especies acuáticas estudadas baixo un enfoque de ACV mediante a avaliación ambiental dos sectores acuícolas galegos do mexillón (*Mytilus galloprovincialis*) e do rodaballo (*Scophthalmus maximus*), identificando os seus puntos ambientalmente críticos e propondo potenciais de mellora. Máis aló da aplicación da metodoloxía de ACV ó sector acuícola, esta tese tamén desenvolve novas tendencias no emprego da ACV, concretamente afonda nos potenciais da aplicación conxunta de ACV e Análise por Envoltura de Datos (DEA polas súas siglas inglesas), e na implementación de estratexias de avaliación da pegada de carbono (CF polas súas siglas en inglés).

A tese divídese en once capítulos recollidos en cinco seccións. A primeira sección abrangue os dous primeiros capítulos, nos que se contextualiza o estudo mediante a introdución do sector acuícola e das principais ferramentas de xestión empregadas (ACV, DEA e CF).

A segunda sección céntrase na aplicación da ACV ó sector mexilloneiro galego. Inclúese non só a análise do cultivo de mexillón (Capítulo 3) senón tamén a avaliación do seu procesado e consumo (Capítulo 4), e do tratamento de residuos específicos do sector mexilloneiro (Capítulo 5). Consecuentemente, grazas á ACV acádase unha completa avaliación ambiental dos tres produtos clásicos de mexillón: mexillón fresco, mexillón en conserva e mexillón conxelado.

A terceira sección comprende a avaliación mediante ACV do sector acuícola do rodaballo en Galicia. Primeiramente, lévase a cabo un estudo de ACV para a produción de pensos de acuicultura (Capítulo 6) xa que é sabido que estes pensos resultan ser un elemento clave no comportamento ambiental das plantas acuícolas. Tras elo, o Capítulo 7 integra a ACV dos pensos mariños no caso de estudo do cultivo e consumo de rodaballo.

A cuarta sección resérvase ó desenvolvemento e aplicación de metodoloxías intimamente ligadas á ACV. Así, abórdase o uso conxunto de ACV e DEA, mostrándose ademais a súa aplicación no caso da miticultura (é dicir, no cultivo de mexillón) baixo dúas perspectivas diferentes: eficiencia operacional (Capítulo 8) e eficiencia ambiental (Capítulo 9). Por outra parte, o Capítulo 10 exemplifica o cálculo da pegada de carbono empregando para elo un produto típico de mexillón en conserva e as pautas propostas pola especificación PAS 2050, que estase a consolidar como metodoloxía de referencia para a avaliación de pegadas de carbono.

A quinta sección componse dun único capítulo (Capítulo 11) onde se recollen as conclusións xerais derivadas desta tese de doutoramento.

Os mexillóns son o produto estrela da acuicultura galega. Este molusco bivalvo cultívase en bateas segundo un procedemento acuícola extensivo que require un mínimo control por parte do cultivador e que non precisa de aporte externo de nutrientes nin da participación durante o proceso reprodutivo. As bateas galegas producen o 98% dos mexillóns cultivados en España. O Capítulo 3 recolle a primeira ACV levada a cabo para a fase de cultivo de mexillón. Con este fin, estudáronse as principais áreas produtivas galegas. Os datos de inventario obtivéronse de entrevistas e enquisas realizadas para un conxunto de embarcacións que conta coa produción de máis de sete mil toneladas de mexillón. A caracterización ambiental incluíu as seguintes categorías de impacto: esgotamento dos recursos abióticos, quentamento global, esgotamento da capa de ozono, toxicidade humana, ecotoxicidade (mariña, de auga doce e terrestre), formación de oxidantes fotoquímicos, acidificación e eutrofización. Os resultados desta caracterización revelaron a importancia de considerar non só os aspectos operacionais, senón tamén os bens capitais (instalacións e equipos). O consumo de diesel para a operación da embarcación resultou se-lo principal motivo dos impactos ambientais potenciais, xunto co uso de enerxía e ferro para os bens capitais. Non obstante, necesitaríase un estudo máis pormenorizado dos bens capitais.

O cultivo de mexillón dá lugar a un complexo sectorial que non só inclúe as actividades acuícolas senón tamén un entramado de actividades ligadas ó procesado do mexillón. A este respecto, ademais do subsector de cultivo de mexillón, pódense distinguir tres subsectores en función dos centros onde ten lugar a transformación do mexillón: (i) subsector das estacións depuradoras de moluscos, (ii) subsector das empresas conserveiras, e (iii) subsector dos cocedoiros de mexillón e empresas conserveiras parciais (é dicir, conserveiras que reciben a vianda de mexillón xa cocida). O Capítulo 4 inclúe a avaliación mediante ACV do procesado e consumo de mexillón. A elaboración e uso de inventarios exhaustivos conduciu á caracterización ambiental do sector mexilloneiro en termos da contribución de cada un dos subsectores ós impactos ambientais potenciais. Neste sentido, o subsector das estacións depuradoras de moluscos (responsables da provisión de mexillón fresco) contou coas maiores contribucións, claramente por diante do subsector de cultivo. Os subsectores das empresas conserveiras e dos cocedoiros de mexillón presentaron unhas contribucións moito menores. Os potenciais de mellora propostos destacaron a necesidade de minimiza-lo consumo de enerxía eléctrica nas estacións depuradoras de moluscos. Por outra parte, levouse a cabo unha ACV comparativa coa finalidade de contrasta-lo perfil ambiental dos tres principais produtos de mexillón. Así, esta análise concluíu que os mexillóns frescos comportan un perfil ambiental máis desfavorable cando son comparados cos mexillóns en conserva e cos mexillóns conxelados.

O procesado de mexillón orixina unha serie de residuos específicos da industria mexilloneira. Entre estes residuos, destacan a cuncha de mexillón e os restos orgánicos de mexillón. O Capítulo 5 trata a xestión tanto da cuncha coma dos restos orgánicos de mexillón dende un enfoque de ACV. Por unha parte, procedeuse á caracterización ambiental da valorización da cuncha de mexillón para producir carbonato cálcico. Consecuentemente, o consumo de propano e enerxía eléctrica, a xestión do lodo e as cinsas, o transporte e as emisións atmosféricas foron identificados como os puntos ambientalmente críticos onde deberían centrarse os potenciais de mellora. Neste sentido, realizouse a avaliación ambiental dun escenario futuro para estima-las consecuencias ambientais potenciais no caso de adoptar tres medidas concretas: uso de glicerina en vez de propano, consideración das cinsas de proceso como un produto e non como un residuo, e valorización do lodo. A ACV amosou que tal escenario futuro podería supor un peor desempeño ambiental con respecto á situación actual, a menos que soamente se adoptasen as medidas concernentes ás cinsas e ó lodo. Ademais, avaliouse ambientalmente a conveniencia da valorización da cuncha de mexillón en comparación con outras alternativas para a xestión de residuos (vertedoiro e incineración). A incineración resultou se-la opción menos favorecida, mentres que optar polo envío a vertedoiro podería implicar un mellor desempeño ambiental pero suporía problemas de ocupación de terreo e desvantaxes socioeconómicas. Por outra parte, caracterizouse tamén a valorización dos restos orgánicos de mexillón para producir paté. A raíz desta caracterización, chegouse á recomendación de melloras centradas na proporción dos ingredientes (minimización do consumo de aceite, leite en po, aromas e especias) así como na optimización loxística (transporte do paté) e enerxética (enerxía calorífica). A implementación dos sistemas de valorización das cunchas e dos restos de mexillón dentro do caso de estudio xeral do mexillón revelou que estes sistemas de xestión si que contribúen ós impactos ambientais potenciais, pero cuns valores de caracterización inferiores ós correspondentes ó cultivo e ó procesado de mexillón.

Aínda que a acuicultura extensiva do mexillón domina a acuicultura galega, a acuicultura intensiva de peces mariños tamén goza dun papel relevante, con niveis de produción próximos ás seis mil toneladas anuais. A acuicultura de rodaballo é responsable do 95% da produción e facturación vinculadas á acuicultura intensiva galega. Así, o cultivo de rodaballo en Galicia supón máis do 25% da facturación económica acuícola autonómica, e proporciona arredor do 90% da produción española de rodaballo de acuicultura. Os capítulos 6 e 7 abordan a ACV da acuicultura intensiva de rodaballo. Dende un punto de vista ambiental, é sabido que os pensos de uso acuícola constitúen un aspecto clave en canto á súa contribución ós impactos ambientais potenciais. Por elo, o Capítulo 6 baséase en levar a cabo unha ACV para a produción de pensos destinados a acuicultura, abarcando tanto pensos para acuicultura intensiva mariña coma pensos para acuicultura intensiva continental. A formulación dos pensos resultou se-lo foco onde centra-las accións de mellora. Por tanto, os produtores de pensos deberían avalia-la utilización de novos ingredientes ou o emprego de diferentes proporcións na súa formulación. O desenvolvemento dunha ACV detallada para os pensos acuícolas mariños permitiu a súa implementación no seo da ACV para o cultivo e consumo de rodaballo, que foi o obxecto de estudo do Capítulo 7. A caracterización ambiental da acuicultura galega de rodaballo conduciu á identificación do consumo eléctrico nos criadeiros de rodaballo como o principal punto crítico, por diante do consumo de pensos e diesel nas plantas de engorde. Ademais, estableceuse unha comparación aproximada entre acuicultura intensiva e acuicultura extensiva tomando como referentes o cultivo de rodaballo e mexillón, respectivamente; e adoptando como unidade funcional un mesmo aporte proteínico. Consecuentemente, de xeito xeral, o sector acuícola extensivo (mexillón) amosou un peor comportamento ambiental có sector acuícola intensivo (rodaballo).

A aplicación da ACV ós sectores acuícolas do mexillón e do rodaballo en Galicia demostrou a capacidade desta ferramenta para proporcionar transparencia e trazabilidade ó longo da cadea comercial de mexillóns e rodaballo. Non obstante, esta tese non só aplica a metodoloxía da ACV, senón que tamén desenvolve e discute novas tendencias no emprego da ACV, coma a aplicación conxunta de ACV e DEA, e a avaliación de pegadas de carbono (CF).

A DEA é unha metodoloxía empregada para cuantifica-la eficiencia produtiva de múltiples entidades similares. Para levar a cabo unha DEA, deben coñecerse os datos das principais entradas e saídas de cada unha das entidades. A partir destes datos, esta ferramenta formula e resolve un modelo de optimización que facilita o benchmarking do desempeño operacional de cada entidade avaliada. A DEA discrimina os puntos operacionalmente ineficientes e propón melloras tecnoloxicamente plausibles baixo a perspectiva dunha actuación operacional eficiente. Por outra parte, os impactos ambientais dependen da eficiencia coa cal se executan as operacións. No caso de dispor dos datos de inventario de ciclo de vida para múltiples instalacións similares, entón poderíase realiza-lo benchmarking do desempeño operacional de cada instalación mediante DEA. Os capítulos 8 e 9 desenvolven o uso sinérxico de ACV e DEA como un enfoque metodolóxico que liga a eficiencia operacional e os impactos ambientais. En particular, o Capítulo 8 propón o método ACV+DEA de cinco pasos como unha metodoloxía que aglutina o benchmarking operacional, a verificación de ecoeficiencia e a avaliación dos impactos ambientais potenciais. Este método aplicouse a unha ampla mostra de bateas de mexillón a fin de proba-la súa aplicabilidade e utilidade. Consecuentemente, detectáronse as bateas operacionalmente ineficientes e propuxéronse os seus correspondentes valores obxectivo a nivel operacional. O método ACV+DEA de cinco pasos demostrou a dependencia dos impactos ambientais con respecto ó desempeño operacional, e favoreceu a cuantificación dos beneficios potenciais dentro do marco conceptual da ecoeficiencia.

A aplicación conxunta ACV+DEA permite conxuga-las fortalezas e minimiza-las debilidades de ambas metodoloxías de xeito que se acada un efecto sinérxico e asemade mantense un carácter cuantitativo. Os métodos ACV+DEA presentan as vantaxes de evita-la utilización de inventarios promedio (eludindo, por tanto, as desviacións estándar asociadas) e de engadir unha dimensión económica (operacional) á análise ambiental. Estas vantaxes conséguense mediante a aplicación do método ACV+DEA de cinco pasos, pero tamén se obteñen ó aplica-lo método ACV+DEA de tres pasos que se desenvolve no Capítulo 9. Este segundo enfoque de tres pasos permite determina-la eficiencia ambiental así como estimar directamente os impactos ambientais potenciais obxectivo. A súa aplicabilidade foi tamén demostrada no caso das bateas de mexillón. Así, identificáronse as bateas operacional e ambientalmente ineficientes, e propuxéronse directamente as melloras plausibles tanto nos consumos operacionais coma nos impactos ambientais potenciais. Os dous métodos ACV+DEA discutidos poden considerarse de aplicación xeral para calquera estudo de ACV sempre e cando se dispoña de datos para múltiples entidades similares.

Por último, a crecente concienciación acerca do cambio climático como un problema de carácter global fai que as grandes empresas estean a solicitar un procedemento estandarizado para a medición e comunicación das emisións de efecto invernadoiro ligadas ós produtos destinados ó consumidor. Neste contexto, o CF erixiuse como a ferramenta de aplicación para a avaliación da pegada de carbono de produtos. Como se discute no Capítulo 10, esta ferramenta resulta de utilidade tanto para as compañías ó longo da cadea do produto coma para os lexisladores.

O CF implica a estimación da cantidade global das emisións de efecto invernadoiro vinculadas a un produto (ben ou servizo) ó longo da súa cadea de abastecemento, incluíndo o seu uso e disposición final. Polo tanto, o termo pegada de carbono refírese ás emisións de efecto invernadoiro dun produto a través do seu ciclo de vida, abranguendo tanto as materias primas coma a produción, distribución, uso por parte do consumidor e a disposición final/reciclaxe. Como gases de efecto invernadoiro inclúense o dióxido de carbono, o metano e o óxido nitroso, xunto con familias de gases que comprenden os hidrofluorocarbonos e os perfluorocarbonos. Non obstante, o CF non debería entenderse coma unha simple ACV restrinxida á categoría de impacto de quentamento global dado que o seu recente auxe está promovendo a construción dun marco metodolóxico sólido que garanta o poder de comparación e comunicación. A este respecto, a especificación PAS 2050 proporciona un método de aplicación xeral para o CF dun produto; a aceptación desta especificación prevese ampla. O Capítulo 10 emprega o caso de estudo do mexillón para exemplificar e discuti-la implementación do CF para un produto típico de mexillón en conserva de acordo coas pautas definidas pola especificación PAS 2050. Ó longo da avaliación da correspondente pegada de carbono, identificáronse as principais fortalezas e debilidades deste enfoque, proporcionando simultaneamente un punto de partida para que os procesadores de mexillón e os lexisladores se beneficien das vantaxes que comporta a utilización responsable do CF. Así, o CF probou ser unha ferramenta útil para a avaliación interna das emisións de efecto invernadoiro ó longo do ciclo de vida do produto. Ademais, a súa aplicación conduciu á identificación de puntos susceptibles de mellora. Por tanto, o CF preséntase como un interesante apoio para a toma de decisións no seo das compañías. Sen embargo, é certo que o CF aporta unha visión limitada do desempeño ambiental dun produto debido a que só avalía unha única categoría de impacto (o quentamento global). Mentres que isto constitúe un importante inconveniente, a gran fortaleza do CF radica no emprego dun enfoque de ciclo de vida e na súa crecente popularidade. Isto fai posible a elaboración de políticas que promovan a implementación de estratexias de CF e sirvan así de vehículo provisional cara un marco político integral para a avaliación ambiental de produtos en base ó seu ciclo de vida.

Annex III

Curriculum Vitae

Personal data	
Name	Diego Iribarren Lorenzo
Date of birth	14 December 1982
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Academic background	
December 2005	Chemical Engineering Degree. School of Engineering. University of Santiago de Compostela (Spain)
September 2008	Master Thesis. Chemical Engineering Department. School of Engineering. University of Santiago de Compostela (Spain)
March 2010	Doctoral Thesis. Chemical Engineering Department. School of Engineering. University of Santiago de Compostela (Spain)

Research stays

Chemical Engineering Department. University of Oviedo (Spain). September-December 2009

Scholarships

Collaboration grant. Department of Chemical Engineering. School of Engineering. University of Santiago de Compostela (Spain). Spanish Ministry of Education. Academic year 2004-2005

Assistant grant. Department of Chemical Engineering. School of Engineering. University of Santiago de Compostela (Spain). October 2005-January 2006

Sustainability grant. Department of Chemical Engineering. School of Engineering. University of Santiago de Compostela (Spain). December 2005-February 2006

Doctoral grant. Department of Chemical Engineering. School of Engineering. University of Santiago de Compostela (Spain). Xunta de Galicia. October 2006-April 2007

FPU scholarship. Department of Chemical Engineering. School of Engineering. University of Santiago de Compostela (Spain). Spanish Ministry of Education (Training Program for University Teachers). May 2007-April 2011

Participation in research projects

Evaluación ambiental e innovación tecnológica en sectores alimentarios estratégicos mediante el análisis de ciclo de vida. Xunta de Galicia (PGIDIT04TAL269003PR)

Potenciación y afianzamiento competitivo de recursos de uso industrial. Interreg project (SP1.E 185/03)

Hacia una acuicultura sostenible – ACUISOST. CENIT project

Capacity Building of Thai food industries on carbon footprint labelling to promote the development of low-carbon trade between EU and Thailand for climate change mitigation. European Union project (DCI-ASIE/2008/158-380)

Finding regional environmental life cycle information on packaging waste management through flexible software tools and databases. LIFE project (LIFE09 ENV/E/000135)

Courses

1. *Certificado de Aptitud Pedagógica (C.A.P.).* Educational Science Institute (ICE). University of Santiago de Compostela (Spain). October 2006-March 2007

2. *"Biopelículas, ciencia y tecnología: estado del arte".* Prof. Dr. Eng. Luís Melo (Chemical Engineering department, University of Porto). School of Engineering. University of Santiago de Compostela (Spain). 8-12 May 2006

3. *"Aplicación práctica del modelado para el diseño y operación de procesos de eliminación de N y P en unidades de lodos activos y de biopelículas".* Prof. Dr. Eng. Luís Larrea (CEIT, San Sebastián). School of Engineering. University of Santiago de Compostela (Spain). 18-19 May 2006

4. *"Actividades de apoyo al sector productivo en temas ambientales: Interdisciplinaridad y eficacia".* Prof. Dr. Eng. Gladys Vidal (EULA, University of Concepción, Chile). School of Engineering. University of Santiago de Compostela (Spain). 13-15 February 2007

5. *"Curso práctico de introducción y programación de PLCs".* Francisco del Prado Rentero (Siemens). School of Engineering. University of Santiago de Compostela (Spain). 13, 15, 20 and 22 March 2007

6. *"Consumo y medio ambiente".* Xunta de Galicia and Gas Natural Foundation. Santiago de Compostela (Spain). 29 March 2007

7. *"Environmental Thermodynamics".* Prof. Dr. Eng. Robert Kleerebezem (Environmental Engineering department, Delft University). School of Engineering. University of Santiago de Compostela (Spain). 21-25 May 2007

8. *"Modelling and observer design in biological processes".* Dr. Eng. Olivier Bernard (INRIA, France). School of Engineering. University of Santiago de Compostela (Spain). 28 May-1 June 2007

9. *"Introduction to the rheology of complex fluids".* Prof. Dr. Loïc Hilliou (Chemical Engineering department, University of Porto). School of Engineering. University of Santiago de Compostela (Spain). 18-20 June 2007

10. *"Ecodiseño".* Prof. Dr. Joan Rieradevall (Chemical Engineering department, Autonomous University of Barcelona). School of Engineering. University of Santiago de Compostela (Spain). 26-29 June 2007

Courses (cont.)

11. *"Desarrollo ambiental sostenible en Austria"*. Dr. Eng. Karl E. Lorber (Institute for Sustainable Waste Management and Technology, University of Leoben). School of Engineering. University of Santiago de Compostela (Spain). 13-14 September 2007

12. *"Tecnología de alimentos: un enfoque multidisciplinario a su problemática presente y futura"*. Prof. Dr. J. Antonio Torres (Food Process Engineering Group, Oregon State University). School of Engineering. University of Santiago de Compostela (Spain). 27 September 2007

13. *"II Xornadas sobre Sustentabilidade no Sector Pesqueiro Galego: Retos da Miticultura"*. Advanced Studies Centre (CEA). University of Santiago de Compostela (Spain). 26 October 2007

14. *"Modelos de calidad del aire"*. Prof. Ana Isabel Miranda (University of Aveiro). School of Engineering. University of Santiago de Compostela (Spain). 21-23 January 2008

15. *"Inventarios de emisiones atmosféricas"*. Dr. Carlos Borrego (University of Aveiro). School of Engineering. University of Santiago de Compostela (Spain). 11-13 June 2008

16. *"Technical workshop on carbon footprint labelling of food products: Carbon footprint analysis and management"*. Centre for Environmental Strategy (CES). University of Surrey, Guildford (UK). 20-22 October 2008

17. *"VII Reunión de la Red Temática de ACV"*. School of Engineering. University of Santiago de Compostela (Spain). 7-8 June 2009

18. *"Biorremediación de aguas ricas en arsénico y biorremediación de aguas de drenajes ácidos de minas"*. Prof. Dr. Jim Field and Prof. Dr. Reyes Sierra (University of Arizona). School of Engineering. University of Santiago de Compostela (Spain). 21 July 2009

Conferences

1. "The application and assessment of Control Station software for education in chemical engineering". P.M. Bello, *D. Iribarren*, M.C. Barros, J.A. Souto. International Technology, Education and Development Conference, Valencia (Spain), 7-9 March 2007. INTED2007 Proceedings (ISBN: 84-611-4517-8). IATED, 2007

2. "Practicals development for the teaching of Instrumentation and Control of Chemical Processes in Chemical Engineering Degree". P.M. Bello, *D. Iribarren*, J.A. Souto, M. González. International Technology, Education and Development Conference, Valencia (Spain), 3-5 March 2008. INTED2008 Abstracts Book (ISBN: 978-84-612-0192-1) & INTED2008 Proceedings (ISBN: 978-84-612-0190-7). IATED, 2008

3. "Combined use of process simulator and EMFA software for plant environmental design in chemical engineering degree". *D. Iribarren*, P.M. Bello. International Technology, Education and Development Conference, Valencia (Spain), 3-5 March 2008. INTED2008 Abstracts Book (ISBN: 978-84-612-0192-1) & INTED2008 Proceedings (ISBN: 978-84-612-0190-7). IATED, 2008

4. "Binomio eficiencia operacional-impactos ambientales en miticultura". *D. Iribarren*, M.T. Moreira, G. Feijoo. Congreso Medio Rural y Cambio Climático, A Coruña (Spain), 26 March 2009

5. "Linking fuel consumption and eco-efficiency in fishing vessels. A brief case study on selected Galician fisheries". I. Vázquez-Rowe, *D. Iribarren*, A. Hospido, M.T. Moreira, G. Feijoo. 1st International Symposium on Fishing Vessel Energy Efficiency, Vigo (Spain), 18-20 May 2010

6. "A double perspective on the joint implementation of Life Cycle Assessment and Data Envelopment Analysis". I. Vázquez-Rowe, *D. Iribarren*, M.T. Moreira, G. Feijoo. SETAC Europe 20th Annual Meeting, Seville (Spain), 23-27 May 2010

7. "Estimating the carbon footprint of the Galician fishing sector (NW Spain)". *D. Iribarren*, I. Vázquez-Rowe, A. Hospido, M.T. Moreira, G. Feijoo. 7th International Conference on Life Cycle Assessment in the Agri-Food Sector, Bari (Italy), 22-24 September 2010

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Other interesting data

Master in Prevention of Labour Risks, Quality and Environmental Management. Centro de Iniciativas Profesionales. Santiago de Compostela (Spain). October 2007-June 2008

Contract of employment. Institute of Technology. University of Santiago de Compostela (Spain). June-December 2006

Award for one of the five best academic records in Chemical Engineering. School of Engineering. University of Santiago de Compostela (Spain)

Special award in Chemical Engineering degree. University of Santiago de Compostela (Spain)

Acronyms

Acronym	Concept	Acronym	Concept
ADP	Abiotic Depletion Potential	*HTP*	Human Toxicity Potential
AP	Acidification Potential	*LCA*	Life Cycle Assessment
CF	Carbon Footprinting	*LCI*	Life Cycle Inventory
CRS	Constant Returns to Scale	*LCIA*	Life Cycle Impact Assessment
DEA	Data Envelopment Analysis	*LP*	Linear Program
DMU	Decision Making Unit	*METP*	Marine aquatic Eco-Toxicity Potential
EP	Eutrophication Potential	*ODP*	Ozone layer Depletion Potential
ERM	Enhanced Russell graph Measure	*POFP*	Photochemical Oxidant Formation Potential
FETP	Fresh water aquatic Eco-Toxicity Potential	*PPS*	Production Possibility Set
FU	Functional Unit	*SBM*	Slacks Based Measure
GHG	GreenHouse Gas	*TETP*	Terrestrial Eco-Toxicity Potential
GWP	Global Warming Potential	*VRS*	Variable Returns to Scale

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