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Cleaner production strategies to reduce greenhouse gas emission in the Western Australian finfish industry

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Abstract

A unique research program was developed to measure greenhouse gas emissions (GHG) from three Western Australian finfish supply chains, and to determine a combination of strategies that have the potential to reduce up to 35 % of the total GHG emissions. The areas of the greatest greenhouse gas (GHG) emissions from three Western Australian finfish supply chains were identified using a partial life cycle assessment (PLCA). Potential cleaner production strategies (CPSs) to reduce those GHG emissions were then developed and assessed for their potential GHG emission reduction, impact on the capital and production costs, and impact on product quality.

The following objectives were addressed in this research:

1. Identify the areas of greatest greenhouse gas emissions from selected Western Australian seafood supply chains
2. Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs
3. Recommend intervention strategies to reduce the greenhouse gas emissions from the Western Australian finfish supply chain

A PLCA was used to assess the current greenhouse gas emissions in three Western Australian finfish supply chains from a trawl harvest: a regional supply chain with a processor and retailer in a regional location, an independent supply chain where the processing occurs in the retail outlet and a supply chain with a city processor and supermarket. Results indicated electricity, refrigeration gases and filleting waste had the greatest greenhouse gas emissions in all supply chains measured. The regional supply chain also utilised polystyrene packaging with a higher greenhouse gas emission than the cardboard boxes utilised in the major supply chain.

Potential CPSs were then developed to reduce the greenhouse gas emissions from electricity consumption, refrigeration gases, filleting waste and polystyrene packaging. Each CPS was modelled to understand the greenhouse gas emissions (using a PLCA), the cost (using a cost benefit analysis and GHG reduction per $ 1 of capital investment), and where appropriate, the impact on product quality (using temperature, drip loss, quality index, microbiology and texture measurements). The potential greenhouse gas emissions and economic implications differed between supply chains due to the quantity of fish each supply chain received and consequently, the quantity of filleting waste, the initial electricity consumption, the location of each facility and whether facilities owned or leased their refrigeration equipment.

Solar electricity provided the greatest potential GHG emission reduction and potential long term profit in both the regional processor and independent retailer. Although solar electricity also provided a GHG reduction and potential profit in the city processor, biogas production from fish waste had a larger potential GHG reduction.

This research was a unique study in combining LCA, economic and quality analyses, measuring and recommending cleaner production strategies within the whole finfish fillet supply chain in Western Australia. Further research on the supply chains analysis is recommended to measure the actual implications of the CPSs incorporated.

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List of Publications Relevant to the Thesis

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Denham F., Biswas W., Howieson J., Solah V. (2015) Development of cleaner production strategies for Western Australian finfish supply chains. World Seafood Congress in September 2015, Grimsby, UK (accepted presentation).

Denham F., Howieson J., Biswas W., Solah V., (2015) Carbon footprint in seafood retail. The Australian Seafood Retailers Network Seminar. Sydney (invited presentation)

Denham F., Biswas W., Howieson J., Solah V. (2013) Environmental impact of a finfish supply chain in Western Australia: analysis, interventions and opportunities. The Australian Life Cycle Assessment Society Conference, Manly (poster).

Abbreviations and Glossary

Terms Used	Definitions
By-catch	Unwanted marine creatures that are caught in the nets while fishing for another species
CH_4	Methane
CPSs	Cleaner production strategies – operational changes implemented by industry to reduce the impact per metric tonne of product
CO_2	Carbon dioxide
Eco-efficiency	Increasing production using fewer resources
GHG	Greenhouse gases – emissions including: CO_2, CH_4 and N_2O
HACCP	Hazard Analysis and Critical Control Points – a quality control system used to identify and prevent chemical, biological and physical contamination in the food industry
kg	Kilograms – measure of weight
km	Kilometres – unit of distance
kWh	Kilowatt hours – measurement of energy used for electricity – quantity of power (kilowatts) multiplied by the hours used
LCA	Life cycle assessment – evaluates the product throughout its lifespan to determine the possible environmental impact
PLCA	Partial life cycle assessment – life cycle assessment that does not take into account the entire supply chain (e.g. does not include input production)
Cost benefit analysis	Method of valuing an investment over a certain time period in the current value of money

Terms Used	Definitions
LCC	Life cycle cost – the cost of acquisition, ownership and disposal of a product over a defined period of its life cycle Sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system. In includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life.
LCI	Life cycle inventory – inventory of input/output data with regards to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study. Sorts into how much emissions and what type. Does give basis of comparison
N_2O	Nitrous oxide
Sustainability	Meeting 'the needs of the present without compromising the ability of future generations to meet their own needs'
Sustainable supply chain management	Working as a whole supply chain with the intention of reducing life cycle environmental impact, enhancing social equity and saving costs
tkm	Tonne kilometres – used to calculate the emission factor of transporting 1 tonne, 1 kilometre $\text{tkm} = \frac{\text{kg of input/output}}{\text{kg of fish}} \times \frac{\text{km travelled}}{1\ 000}$

Table of Contents

Table of Figures

Table of Tables

CHAPTER 1. General Introduction

1.1. Introduction

The aim of this thesis was to:

- measure the greenhouse gas (GHG) emissions from three Western Australian finfish supply chains,
- find the areas of greatest emissions using a partial life cycle assessment and
- develop and assess (for their potential GHG reduction, impact on costs, and product quality) potential cleaner production strategies (CPSs).

1.2. Australian seafood industry

The seafood industry is an important primary production industries in Australia, with harvest quantities reaching 233,119 metric tonnes in 2012-13 (ABARES, 2014). Seafood comprises five percent of all food production in Australia (DAFF, 2014) and is worth $ 2.4 billion (2012-13), with $ 1.2 billion of this exported (ABARES, 2014).

The Western Australian seafood industry harvested 20,378 metric tonnes of seafood in 2012-13, including 10,351 metric tonnes of fish (ABARES, 2014). As Western Australia is a large state (coastline spans 12,889 km (Australian Government - Geoscience Australia, 2015)), its' waters vary in temperature from 15-32 °C (Department of Fisheries, 2014). Therefore, the 132 species assessed by the Department of Fisheries (2014) in Western Australia include both tropical and cold water finfish species and are selected for commercial use by consumer demand. The species with the highest harvest in 2013-14 were Australian sardine (*Sardinops sagax*), Goldband snapper (*Pristipomoides multiden*), Australian herring (*Arripis georgianu*), Red emperor (*Lutjanus sebae*) and Crimson snapper (*Lutjanus erythropterus*) (Department of Fisheries, 2014).

The Western Australian seafood industry uses several different methods to harvest fish, including trawling, purse seining, line and long lining and trapping. Trawling involves dragging a net behind the vessel to harvest fish; a purse seine is a large net that is cast over the side of the vessel and gathers into a purse shape when pulled; line and long lining vessels shoot baited hooks off the end of the vessel to harvest fish and; in trap fishing large baited cages are dropped off the side of the vessel.

Once the fish is caught, it is transported to the nearest capital city; Perth. Due to the large size of the state, this could be up to 2,000 km, depending on the port location.

Consequently, the Western Australian seafood industry is unique in the varying species, and the remote location of both the port and Perth from other cities in Australia.

1.3. Environmental supply chain management in the seafood industry

Environmental supply chain management is defined as working as a whole supply chain with the intention of reducing life cycle environmental impact, enhancing social equity and saving costs (Erol et al., 2011). A whole of chain approach is important in environmental management to ensure efficiency. Analysis of the entire supply chain provides precise data identifying economic and environmental improvement opportunities (Erol et al., 2011).

To incorporate supply chain management in the seafood industry, individual companies need to communicate and develop environmental strategies with their stakeholders to work together to achieve the most efficient use of resources. Meixell and Luoma (2015) classified supply chain stakeholders as primary stakeholders (i.e. customers, suppliers, employees, top managers and shareholders), and secondary stakeholders (i.e. government, non-government organisations, community, media, competitors, trade associations, owners and investors). Primary stakeholders' actions (both environmentally and economically) can filter through to downstream customers (Wognum et al., 2011). As a result, the downstream facilities have the power to undo the benefit of mitigation strategies, as well as finance the cost of the strategy. Therefore, collaboration with the whole supply chain increased both product quality and profit by using the same quantity of resources to meet the demand of the final product, rather than the direct customer (Jensen et al., 2010).

A life cycle assessment (LCA) is one method of evaluating the environmental impact of the supply chain. A LCA evaluates the product throughout its' lifespan to determine the emission generated from production (International Organisation for Standardization, 2006).

Results from LCA studies will highlight areas of greatest environmental impact where CPSs may be implemented. CPSs are operational changes implemented by industry to reduce the impact of seafood production (as measured by LCA) and are referred to in the following categories as described by UNEP (2002):

1. Good housekeeping: requiring no specialized skills, just needs common sense;
2. Input substitution: replacing resources with environmentally preferred substances;
3. Technological modification: modifying existing structures to increase efficiency;
4. Product modification: modifying a product to reduce material consumption and to enhance recyclability and;
5. Recycling waste.

The environmental impact of the Australian seafood industry is a new area with little research. Instead, the focus is on fish stocks and marine parks (Department of Fisheries, 2014) incorporating an environmental supply chain management assessment of the seafood industry should broaden this focus, including: the quantity of fish harvested; atmospheric emissions and waste generation; employee safety and job security (although not covered in this study); a constant supply of fish; consistent quality of fish; and the profitability of the business (Standal and Utne, 2011). In short, the responsibility to maintain environmental supply chain management belongs to all stakeholders in the seafood supply chain, as both primary and secondary stakeholders have the power to influence these decisions.

However, with little LCA research in the Australian seafood industry, the ability to maintain the environmental supply chain management is limited to the customers' demands, bringing it back to what is covered in Australian media – fish stocks and marine parks. Therefore, further research to understand the environmental impact of the Western Australian seafood supply chain is required.

1.4. Greenhouse gas emissions in the seafood supply chain

This study focusses specifically on the GHG emissions from the finfish supply chain. GHGs are a combination of methane, carbon dioxide and nitrous oxide that create global warming potential (GWP), a means of comparing the impact of climate change over a specified period (e.g., 100 years), in a unit relative to CO_2, including methane, nitrous oxide and carbon dioxide (Forster et al., 2007).

Although the seafood industry is not specifically mentioned in the national GHG accounts, the food and beverage industry (including seafood) GHG emissions have risen steadily since 1995, with a major jump in 2010 (Department of the Environment, 2015b). Furthermore, the national GHG account results for commercial refrigeration (an important factor in all stages of seafood handling) has risen exponentially since 1995, despite a slight fall in total GHG emissions from Australia over the same time period (Department of the Environment, 2015b), indicating the seafood industry (and other intensive cold chains) have increased their GHG emissions significantly, compared to a GHG reduction in other industries.

The introduction of the carbon tax in 2012, added to the price of energy in all sectors of the supply chain (Department of the Environment, 2015c) and put pressure on the industry to reduce their 'carbon footprint'. Australia is committed to reporting its' GHG emissions to the United Nations through the National Greenhouse and Energy Reporting (NGER) Act (Office of Parliamentary Counsel, 2014). However, this act only aims at registering high GHG emitters (such as 50 kilo tonnes CO_2 –eq per financial year (Office of Parliamentary Counsel, 2014)), rather than measuring the GHG emissions of all industries. Therefore, this research will provide opportunities to measure and mitigate a non-regulated Australian supply chain where GHG emissions are currently unknown.

Like Finkbeiner et al. (2011), this research considers carbon footprints in terms of an LCA, with the limited focus on one impact category only, i.e. climate change. All methodological requirements and principles of the LCA can be applied to estimate carbon footprints, as evidenced by local and international literature (Biswas, 2013; Biswas et al., 2008; Biswas et al., 2010; Biswas et al., 2011; Finkbeiner et al., 2011; Ghafoori et al., 2006; Grant and Beer, 2008; Gunady et al., 2012). The partial LCA is used in this study to mitigate the need in Australia to meet global GHG emission targets.

Therefore, Australian industries require targeted strategies to reduce current GHG emissions. Previous seafood studies have focussed on the environmental impact of one stage of the supply chain (Boissy et al., 2011; Claussen et al., 2011; Hobday et al., 2011; Parker and Tyedmers, 2012b; Svanes et al., 2011b; Vázquez-Rowe et al., 2010b; Wakeford, 2010) without considering the remaining supply chain stages. When the environmental impact in the supply chain as a whole was measured by Vázquez-Rowe et al. (2011b) and Winther et al. (2009), there was no assessment of CPSs. A LCA study by Hobday et al. (2014) covered the whole seafood supply chain in Australia, but this study did not represent the species, processes and transport distances associated with Western Australian finfish.

Whilst fish is a protein product, its handling, processing and thus, GHG emissions differ from other protein products in Australia. For example, the meat industry have traditionally sold all portions of the beef carcass including tongues, brains, sweetbreads, hearts and livers for edible products and hide (leather), fats (cosmetics) and bones (pet food) (Hui, 2012). The seafood industry in Australia is not yet utilising all its waste, and is one of the few industries utilising wild products. Therefore, these differences in processing and handling make fish GHG emissions different to other meat products.

As a result, this study aimed to understand the GHG emissions from a whole Western Australian finfish supply chain; specifically the areas of greatest GHG emissions, and how potential CPSs might influence GHG emissions, costs and product quality.

1.5. Significance

This research will identify if the Western Australian finfish supply chain is a significant GHG emitter. The national GHG accounts (Department of the Environment, 2015b) did not separate the food and beverage industries into individual sectors, but instead provided an overview for the food industry. Therefore, this research will measure the GHG emissions from the whole supply chain to determine the environmental impact the seafood industry has in Western Australia.

Research on the environmental impact and strategies may lead to benefits for the seafood industry. CPSs targeted to reduce the GHG emissions from the seafood industry will create a competitive advantage by increasing efficiency through using the least amount of resources to create the most products will further reduce costs. Each partner will have the benefit of advertising their corporate responsibility strategies to customers. As a result, the project partners will benefit financially (increasing Western Australian seafood competition), consumers may receive cost reductions and the environmental impact will be reduced.

Therefore, this study will enable fishermen, processing facilities and retailers to identify environmental CPSs for fish supply options. Using the findings of this research, the industry will be able to apply CPSs in order to gain competitive advantage. Reduction of the environmental impact will also reduce chemical and energy use in the seafood supply chain. Ultimately, this research will provide comprehensive information for the decision makers and provide a resource to enable environmental supply chain management for the seafood industry.

This study is also unique in combining environmental impacts and their impacts on the economic and quality aspects in industry. Current studies have looked at the relationship between CPS implementation and costs (Bezama et al., 2012; Pagan and Prasad, 2007; Utne, 2009a, b), CPS implantation and product quality (Manzini et al., 2014; Soussana, 2014), and the relationship between costs and product quality (Franca et al., 2010; Lupin et al., 2010; Sharma, 2010). However, no research has yet combined all three, providing a novel approach to the food industry resource use.

1.6. Objectives

The following objectives are addressed in this thesis and outlined pictorially in Figure 1.1:

1. Identify the areas of greatest greenhouse gas emissions from selected Western Australian finfish supply chains
2. Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs
3. Recommend intervention strategies to reduce the greenhouse gas emissions from the Western Australian finfish supply chain

1.7. Research questions

1. What are the greatest sources of greenhouse gas emissions in selected Western Australian finfish supply chains?
2. What CPSs are available to mitigate these greenhouse gases?
3. What are the impacts of implementing these CPSs on product quality and long term costs?

An outline of each chapter is provided in Figure 1.2.

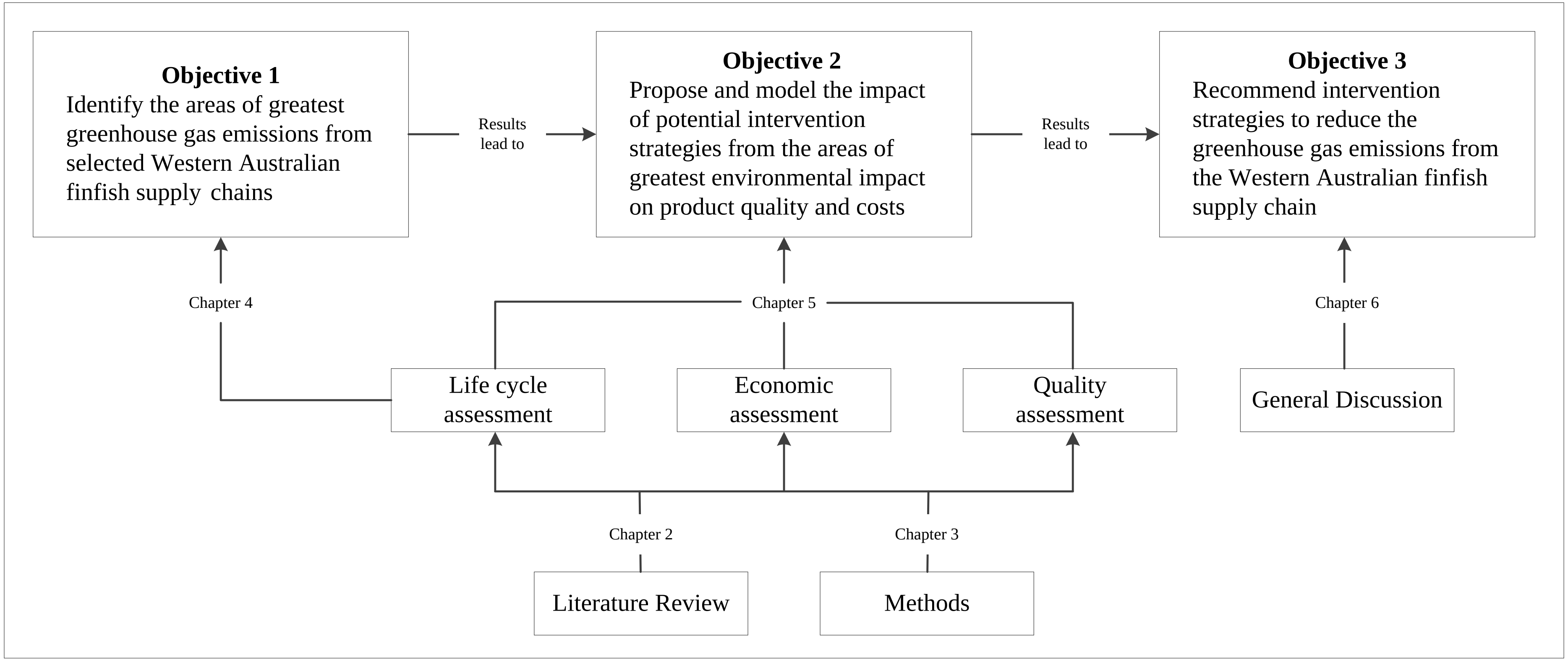

Figure 1.1 Schematic outline of thesis

Chapter 1: Introduction

- Introduces seafood and sustainability
- Project objectives
  - Identify the areas of greatest greenhouse gas emissions from selected Western Australian finfish supply chains
  - Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs
  - Recommend intervention strategies to reduce the greenhouse gas emissions from the Western Australian finfish supply chain

↓

Chapter 2: Literature Review

- Reviews environmental impact assessment methods applied in the food industry
- Discusses the impact of cleaner production strategies on economic and quality aspects and the tools available to measure them
- Paper 1: Environmental supply chain management in the seafood industry: past, present and future approaches

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Chapter 3: Methods

- Description of three finfish supply chains in the study
- Streamline life cycle assessment method for supply chains
- Cleaner production strategy development and resulting assessment methods
  - Streamline life cycle assessment
  - Economic assessment
  - Quality assessment

↓

Chapter 4: The Life Cycle Assessment of the Western Australian Finfish Supply Chain

- Measured the greenhouse gases of the supply chain
- Electricity consumption caused the most GHG emissions in two supply chains
- Refrigerants had the most GHG emissions in the large supply chains

↓

Chapter 5: Identification and Modelling of Cleaner Production Strategies

- Developed potential cleaner production strategies
- Modelled the life cycle assessment, economic and quality impact
- Results differed for each supply chain:
  - Regional supply chain – solar energy
  - City supply chain – solar energy
  - Large supply chain – biogas energy
- Paper 2: Greenhouse gas emissions from a Western Australian finfish supply chain

↓

Chapter 6: General Discussion

- Results were unique due to studying the whole supply chain, fillets and in Western Australia
- Other Australian seafood companies may benefit from the recommendations
- Further research on the outcomes of cleaner production strategy implantation is recommended

Figure 1.2 Summary of each chapter

CHAPTER 2. Literature Review

2.1. Introduction

This chapter reviews environmental impact assessment methods applied in the food industry and the implications of cleaner production strategy (CPS) implementation. This chapter aims to review and justify the selection of the tools and methods which achieve the project objectives one and two (outlined in Figure 1.1):

1. Identify the areas of greatest greenhouse gas emissions from selected Western Australian seafood supply chains
2. Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs.

The specific objectives of this review were to:

1. Define the problem and justify the research
2. Compare and contrast the methods of measuring the environmental impact in the food industry
3. Evaluate economic and quality tools to measure implications of cleaner production strategy implementation and justify the choice selected for the project

2.1.1. <u>Environmental impact in the food industry</u>

The actions of the food industry may result in environmental impact through activities such as processing, waste disposal, chemical use, energy use and transportation. One way to understand the environmental impact is to use an environmental management tool, thereby, analysing a company's efforts to watch and review their environmental footprint (Biswas et al., 2011). Results can also identify potential environmental improvement opportunities for investors (Erol et al., 2011). Consequently, an environmental management system has the potential to demonstrate environmental responsibility to stakeholders.

Each food industry is unique and requires individual research into the environmental impact of each product. Not only do some food products have a rapid turnover due to a short shelf life, but each product has a different environmental impact (Hospido et al., 2010). For example, beef products have higher carbon emissions compared with vegetables due to the manure and enteric fermentation (Thomassen et al., 2008b). The environmental impacts also differ between suppliers of raw materials when factors including type and quantity of inputs used, transport distance and the type of waste generated are considered. Hence, it is important to research each food industry individually to determine the production system with the lowest environmental impact.

Whilst these different outcomes and opportunities from LCA provide different aspects of environmental impact, the Australian government and media have recently focussed on GHG emissions. A “carbon tax” was introduced by the Australian government in 2012 to minimise GHG emissions (Department of the Environment, 2015c). Although this has since been repealed (Department of the Environment, 2015c), the Australian government is pressuring industries to reduce their GHG emissions to keep up with other developed countries (Department of the Environment, 2015a). So far, the government is only pushing for GHG emissions, looking specifically at renewable energy (Department of the Environment, 2015a). The push for cold chains to reduce their ozone depletion has already passed with the phase out of the refrigerant R22 (Department of the Environment, 2014b), enforced by reducing supply and increasing costs of the refrigerant until complete removal in 2029. With the increased energy costs from the carbon tax, and the expectation of government policy pushing renewable energy, this research may assist the seafood industry mitigate these costs through targeted strategies.

When measuring the environmental impact within the food industry, the most effective tool should be applied. Therefore, the following sections review tools applied to monitor the environmental impact within the food industry: measuring energy and water consumption, measuring food miles and using life cycle assessment (LCA).

2.1.2. Measuring energy and water consumption

Energy and water consumption have been measured in processing facilities. Firstly, Bezama et al. (2012) and Pagan and Prasad (2007) successfully involved seafood (Bezama et al., 2012) and a selection of beverage, ginger, salad and vegetable, nut, and bakery processors (Pagan and Prasad, 2007) to monitor and reduce their energy consumption using cleaner production agreements. Following an analysis of energy and water consumption, a set of specific opportunities to reduce the environmental impact were documented, signed by the volunteer processors and the progress monitored by internal (Pagan and Prasad, 2007) and external (Bezama et al., 2012) audits. Documented participant agreements outlined specific objectives including reductions of waste, wastewater, energy and coolant (Bezama et al., 2012). Pagan and Prasad (2007) reported on reductions in water in salad and vegetables; syrups, toppings, blends and mixes and; beverage and vegetable producers (up to $ 65,000 savings per year), energy consumption in salad and vegetables; syrups, toppings, blends and mixes; butter and; ginger producers (up to $ 50,000 savings per year), waste and wastewater in a syrups, toppings, blends and mixes producer ($ 3,500 savings per year), and chemical savings in a salad and vegetables producer ($ 45,000 savings per year) without compromising on product quality. Bezama et al. (2012) measured reduction by percentage in a frozen fish facility, with 24.5 % electricity reduction and 28 % water reduction. Both Bezama et al. (2012) and Pagan and Prasad (2007) attributed these savings to each participating firm's active involvement in monitoring their energy and water consumption.

Although measuring reducing current energy and water consumption is relatively simple for individual firms, it does not necessarily target the areas of greatest environmental impact. Chemical consumption, transport, waste disposal and refrigeration gases are not considered in this type of analysis, excluding potential areas of greatest environmental impacts and costs. Furthermore, the energy and water consumption from suppliers are also excluded. This method is only useful in modifying the current energy and water consumption at an individual facility, rather than modelling the entire environmental impact of the selected process and supply chain.

2.1.3. Measuring food miles

Another method of measuring the environmental impact is recording 'food miles' (metric tonnes of food multiplied by km travelled, represented as tkm). Research by Coley (2011) and Kissinger (2012) calculated the carbon dioxide emitted from food travel by recording the transport method, the product quantity and the distance travelled, resulting in a calculation of the quantity of carbon dioxide emitted per tkm. Identifying the food miles may provide enough evidence to include food transport in food policies instead of a separate transportation policy (Kissinger, 2012).

Focussing only on the distances travelled and the transport mode using food miles as a standardised measure, does not account for the impact of processing, harvesting and retail. Although measuring the impact of transport on the environment is useful, neither Coley (2011) nor Kissinger (2012) assessed the prominent impacts of production and hotspots in their models. If a product has a high impact in transport (for example, travelled from overseas), it does not necessarily account for the impact from processing and transport combined (Coley et al., 2011). Instead, combining both processing and transport data provides a clearer picture. Coley (2011) highlighted that modelling sustainable practices using food miles should not be isolated but instead combined with economic, social and broader environmental measures. So, the food miles tool again only focuses on one part of the production process: transport, potentially ignoring areas of greatest environmental impact unrelated to transport.

2.1.4. Life cycle assessment

LCA is the most widely used method for measuring the environmental impact through evaluating the product throughout its lifespan to determine the possible ecological consequences (International Organisation for Standardization, 2006). The method provides results in many formats, including the global warming potential (the quantity of greenhouse gases (GHGs) or carbon dioxide equivalents), acidification potential (sulphur dioxide equivalents) and eutrophication potential (nitrate or phosphate equivalents) (Hall, 2011a) per functional unit. The functional unit is a reference unit according to the process analysed (International Organisation for Standardization, 2006) for example, a 400 gram package of frozen cod fillets (Ziegler et al., 2003). The LCA approach follows the four steps of ISO 14040-44 (International Organisation for Standardization, 2006) goal, life cycle inventory, impact assessment and interpretation (Figure 2.1).

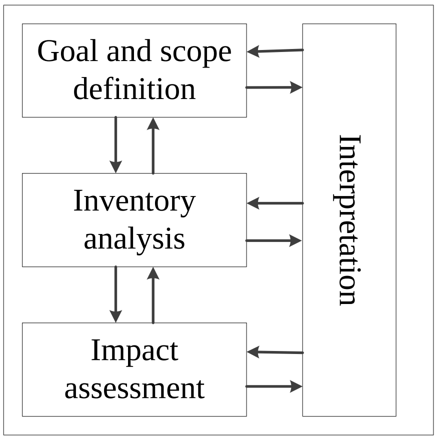

Figure 2.1 Four steps of LCA (International Organisation for Standardization, 2006)

There are different ways of performing LCAs to assess the environmental impacts of food production. A strong connection exists between the choice between attributional LCA and consequential LCA and the choice of how to handle co-products. Insight is needed in the effect of choice on results of environmental analyses of seafood. Attributional LCA is measures how the flows of pollution and resource within a chosen system attributed to the delivery of a specified amount of the functional unit. consequential LCA assesses how pollution and resource flows within a system change in response to a change in output of the functional unit (Thomassen et al., 2008a).

LCA can also be used to develop potential CPSs. CPSs are operational changes implemented by industry to reduce the environmental impact of production and are referred to in the following categories as described by UNEP (2002):

1. Good housekeeping: requiring no specialised skills, just needing common sense
2. Input substitution: replacing resources with environmentally preferred substances
3. Technological modification: modifying existing structures to increase efficiency
4. Product modification: modifying a product to reduce material consumption and to enhance recyclability
5. Recycling waste.

Further discussion of LCA use and CPS specifically implemented in the seafood industry is discussed in Paper 1 in Section 2.7.

LCA can be used to validate the impact of potential CPSs. Thrane et al. (2009a) provided recommendations to two industries and followed up on their progress six years later, determining the changes of the environmental impact over time. Although trialling strategies to determine their environmental impact over time is an accurate method to justify recommendations, it is not necessarily practical. Other researchers have tested strategies concurrently (Claussen et al., 2011; Eide et al., 2003; Pardo and Zufía, 2012; Thomassen et al., 2008b; Vázquez-Rowe et al., 2010b), compared results with similar literature (Iribarren et al., 2010b; Jørgen Hanssen, 1998), or modelled the strategies (Hospido and Tyedmers, 2005; Hospido et al., 2006; Renouf et al., 2011).Whilst comparing strategies concurrently provides reliable results, it involves either using current methods, or implementing changes without validation. Therefore, by modelling the potential savings before implementing CPSs, LCA saves both time and money by validating strategies and demonstrating the impact to industry before implementation.

LCA studies potentially have limitations and scope for error that should be minimised before designing each study. The functional unit definition and the study location set in the system boundaries may specifically affect how the results can be used.

The functional unit, sets the scene for each LCA project. However, Reap et al. (2008) describes potential errors and ways to prevent them when defining the functional unit, including awareness of multiple functions of the products, selecting functions representing actual use of the product, and selecting a unit that can be compared throughout the study. Santero et al. (2011) concurs, finding one particular product description does not fit all. Consequently, the process and purpose of each product in the study should be defined in the early stages to enable a suitable functional unit of comparison.

Furthermore, if LCA studies are to be compared, they must have comparable functional units. Meneses et al. (2012) described the difficulty of relating their results to other published studies, resulting in projects that stand alone, rather than build on others' work. For example, one dairy processing study had a functional unit of one week's milk production (Berlin and Sonesson, 2008) whereas Meneses et al. (2012) had a functional unit of 1 L of milk. Whilst these separate studies were able to draw comparisons within their own research, neither could compare results with the other. Therefore, before each LCA begins, wide reading in the selected research topic is recommended to determine potential studies for comparison and what functional units have already been applied when determining a potential functional unit for each study.

It is also difficult to compare LCA studies from different countries as the emission factors (the average emission rate of a given greenhouse gas (GHG) for a given source, relative to units of activity required) vary. Santero et al. (2011) highlighted the influence of system boundaries, project scope, technology assumptions and production location had on the emission factors in various studies. Duro et al. (2014) demonstrated that the use of coal, gas and oil energy differed between countries and changed over time. So, any production requiring energy (e.g. electricity) would then utilise a different combination of energy sources in its creation depending on where and when it is manufactured. So, all emission factors used in a LCA need to be localised and any comparison between studies needs to account for the potential differences in emission factors utilised.

Consequently, LCA limitations can be reduced by defining the functional unit and system boundaries as well as by choosing emission factors relevant to the country of study. The consideration of these factors before the study begins also defines the extent results can be compared to other studies: either as broad comparison (e.g. had the same hotspot or area of greatest emissions) or comparing specific LCA results.

2.1.5. Method selection

Whilst measuring energy and water use and food miles are simple techniques industry can apply, these methods only provide an indication of the environmental impact of the direct food production process. Using a LCA will measure the emissions from the direct process energy, water and transport as well as the emissions associated with input production and its transportation to the point of use and waste generation. Furthermore, as LCA can be attributional and sequential it can be used to model potential variations such as a change of supplier, or CPS without implementation, rather than measure what has already occurred through monitoring consumption and transport. Attributional LCA has been chosen as this LCA analysis concerns the industry sector of the supply chain rather than investigating the whole life cycle including consumption. Consequently, LCA is the most useful tool in designing a study around developing CPS in the seafood supply chain.

2.2. Understanding the impact of cleaner production strategy implementation

LCA helps to identify potential CPSs and assess the opportunities to reduce the environmental impact. To ensure these CPSs are practical solutions for industry, costs and product quality implications should also be measured. This section discusses specifically how LCA, economic and quality assessments work together in the food (including seafood) industries and why full consideration of all three are recommended before potential CPSs are introduced.

Developing CPSs using LCA may influence the costs and benefits considered in economic analyses. The application of each CPS listed in section 2.2.3 should provide opportunities for reducing costs and increasing profits. UNEP (2002) used the example of a good housekeeping strategy of reducing leaks and spills, increasing the raw material quantities available for production and reducing the costs of these leaks. Cost benefit analysis was used alongside LCA to develop CPSs in European crops, finding input substitution in energy sources both reduce the environmental impact and reduce costs (Torrellas et al., 2012). The recycling waste CPS was coupled with life cycle costs to determine a viable option in a municipal waste management system (Carlsson Reich, 2005). Whilst results indicated no significant cost differences between incineration, composting, recycling and anaerobic digestion, all were cheaper and more environmentally efficient than the landfill option (Carlsson Reich, 2005). Consequently, these economic assessments conducted in conjunction with LCA provide indication of which CPSs are reducing the environmental impact and are also economically feasible for industry to implement.

CPS implementation may also potentially affect the product quality. For example, Andersen (2002) recommended filleting fish early in the supply chain to reduce space transport and storage required, thus, reducing energy and refrigeration emissions. However, storing the fish as fillets, rather than filleting as required resulted in consistent colour, texture and odour deterioration over eight days (Poli et al., 2006). If filleting early in the supply chain is required, freezing or super chilling (storage at -2 °C) the fillets may instead retain the quality (Duun and Rustad, 2007; Viegas et al., 2012). Furthermore, super chilling was found to have a lower drip loss than chilling fillets. Drip loss is moisture leakage of fish over time, resulting in a dryer product, and a reduced weight to be sold. Whilst this initially appears to be a quality issue, many LCA studies use weight as a functional unit: if the product weight decreases over time, the same GHG emissions will be released, but for a smaller quantity of product. If the drip loss is reduced, the final GHG emissions per kg of product then reduces. Therefore, the careful consideration of CPS impact on fillet quality can impact the final emissions.

Product quality is likewise related to the costs and revenue of the seafood company. Although maintaining quality is expensive, losing product results in less to sell. For example, by modelling expiry date management of fresh food, Tromp et al. (2012) noted losses from shelf life management can be potentially reduced by 13.3 %, indicating quality management can increase the portion of sellable product and subsequently, revenue from otherwise wasted product and lower GHG emissions from landfill.

As quality and economic assessments are necessary before implementing any potential CPS, assessment methods are further evaluated to determine the most useful for applying within the current study.

2.2.1. Economic assessments

An economic analysis is vital to prove to firms that running an environmentally sustainable business is financially viable. CPSs can result in cost reduction and resource efficiency, but only if designed to do so (van Berkel, 2007). Consequently, the mitigation strategies developed need to be feasible as well as affordable. To illustrate, if the highest environmental impact of the product measured is resource extraction and refining, then recycling waste products could be beneficial. The waste products can then be used without further extraction and refining, thus creating a greater production capacity for the same amount of environmental damage (Clift and Wright, 2000). Even though the outright environmental damage has not been reduced, the environmental impact per unit of production has. Hence, by increasing efficiency and using resources to their full potential, businesses can become more profitable. Thus, using an economic analysis will provide the costs and feasibility of any changes occurring within the firm. This section discusses three economic analyses that can assess CPSs: cost benefit analysis, life cycle costings and a seafood economic model.

Cost benefit analysis

A cost benefit analysis is a financial tool to determine how lucrative a planned project or financial investment may be (Ridge Partners, 2014). It is used to compare scenarios evaluating costs, benefits and the difference between them (Torrellas et al., 2012), displaying results as net present value (NPV) (the value of an investment over a certain time period in the current value of money was calculated for the comparison). Although cost benefit analysis is a financial tool, it has the flexibility to be applied over many disciplines including lighting (Nassar and Al-Mohaisen, 2006), seafood (Ridge Partners, 2014), agriculture (Torrellas et al., 2012), biofuels (Møller et al., 2014) and health (Thompson et al., 2014). Therefore, it has the ability to assess the financial implications of potential CPSs.

Life cycle cost analysis

Life cycle cost analysis involves the addition of all costs over the life span of a product and is another economic tool available to assess the economic impact of each CPS. Utne (2009a, 2009b) used life cycle cost analysis to measure the costs of potential CPSs within a fishing fleet. Whilst capital, operation, disposal and quality costs were measured, life cycle cost analysis did not quantify offsets to these costs such as potential income, increase in sellable product or cost reduction. Instead, the focus is on the cash outflow, rather than a long term assessment of what benefits potential CPSs can bring.

Individual economic models

A seafood economic model was used to compare the cost benefit of supply chains: a trawling supply chain including three processing facilities and two retailers; and a trawl, trap and line harvest supply chain including two processing facilities, three retail outlets and a regional restaurant (Nath et al., 2011). The model included a series of spread sheets, calculating the costs, income and profit of the product measured from each stage of the supply chain. The purpose of the model was to determine the potential profit changes resulting from the application of mitigation strategies. Therefore, the model demonstrated the current cost of production with the ability to estimate the economic repercussions of implementing mitigation strategies.

Economic assessment and life cycle assessment

Economic assessments may also be used alongside LCA. Shrestha et al. (1998) compared the incremental costs compared to GHG mitigation in potential CPS. This assessment indicated the strategy with the highest potential mitigation opportunity for the lowest capital cost, indicating the cheapest CPS that will mitigate the most GHG emissions.

Method selection

When evaluating potential CPSs, long term costs and profits are important. Life cycle cost analysis only cover the costs of CPSs, ignoring potential profits. Similarly, Nath et al.'s (2011) model does not allow for inflation rates, nor investment discount rates over time as discussed by Department of Treasury (2013) and Ridge Partners (2014), resulting in underestimating the value of the investment. Thus, the model may identify immediate costs and benefits, but like the life cycle cost analysis, fails to accurately model the long term costs and benefits of the CPS. Whilst the cost benefit analysis does not account for different life spans of investments like the LCC, it instead puts all investment opportunities in the same time period for ease of understanding. LCC may compare costs over the life cycle of the investment, but as each investment may differ in life cycle times, this does not provide an easy comparison for those who ultimately make the investment decision: the industry partners. Instead, the cost benefit analysis measures the investment opportunity over a set period of time, includes both potential costs and income that may occur from the CPS and takes into account the inflation rate and discount value of the capital equipment purchased and thus, is applied in this study. Furthermore, the comparison of costs to GHG mitigated used by (Shrestha et al., 1998) provided a simple method to determine which strategy mitigated the most GHG emissions for the cheapest capital outlay. Therefore, the cost benefit analysis provides a generic, long term assessment understood by industry, and the GHG mitigated per cost provides a simple comparison to compare the options both economically and environmentally.

2.2.2. Quality assessment

It is important that that seafood quality is not affected during economic and environmental CPS implementation. Quality assessments are therefore necessary when modelling potential CPSs. However, although LCA and cost benefit analyses are broad tools that can be applied to any industry, quality assessments vary according to the product. As a result, this section is specifically referring to quality assessments within the finfish sector.

Monitoring product quality itself can be a strategy to reduce environmental impact. Quality assurance systems in a processing environment require regular product monitoring, resulting in a higher quality product and fewer rejected products, thus reducing both product and resource wastage (Lupin et al., 2010). By continually monitoring the quality of the fish, aspects the effect the quality such as high storage temperatures can be reduced, thus minimising any unnecessary quality change that may increase the aging of the product. In all stages of the supply chain, poor quality raw materials increase labour costs due to product rejection or reprocessing to meet specifications. Therefore, by managing the product quality from the beginning, the quantity of rejects can be reduced, resulting in a higher yield and reduced waste and thus, a higher efficiency of resources utilisation (Zugarramurdi et al., 2004; Zugarramurdi et al., 2007).

Reducing fish wastage mitigates methane and carbon dioxide emissions released in the anaerobic digestion process which occurs in landfill (Hall, 2011a). Anaerobic digestion is the breakdown process of fish fat, protein and carbohydrates, eventually resulting in methane, carbon dioxide and hydrogen gas emission (Figure 2.2). These emissions can be estimated using the Buswell equation (Symons and Buswell, 1933) which uses the elements in the chemical formula to estimate the methane, carbon dioxide and hydrogen emissions (Equation 2.1). Therefore, minimising the waste to landfill, both from filleting and poor handling can reduce the GHG emissions to the atmosphere.

There are several methods to monitor seafood quality including quality index, microbiological testing, temperature monitoring, biochemical assessments, texture analysis and drip loss.

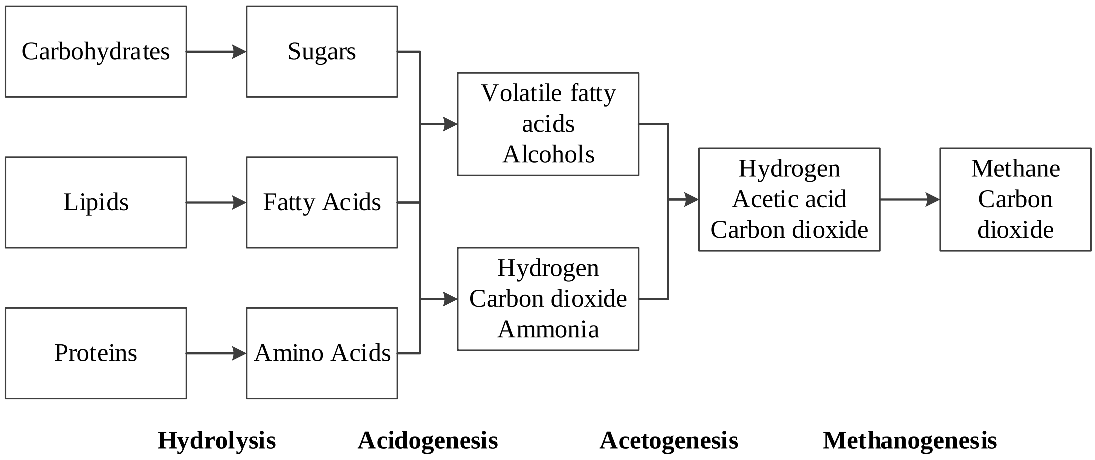

Figure 2.2 Anaerobic digestion process adapted from Hall (2011b)

$$\begin{aligned} & C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \\ & \rightarrow \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{b} + \frac{e}{4}\right) CO_2 + \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 \\ & + d \cdot NH_3 + e \cdot H_2S \end{aligned} \tag{2.1}$$

Quality index

A quality index (QI) is a “recognised readily understandable, rapid, practical, yet scientifically based” (Boulter et al., 2009) method of grading the quality of a product (in this case, fish). A whole fish QI includes the assessment of appearance and texture; eyes; gills; mucus; abdomen and; cut surfaces depending on the species (Boulter et al., 2009). QI is a score system that correlates with optimum storage days on ice (Boulter et al., 2009; Cardenas Bonilla et al., 2007), regardless of the actual age of the fish. It works on the basis that fish spoilage is relative to storage temperature, initially proved by Olley and Ratkowsky (1973) in protein foods generally, and later modelled in seafood (Mejlholm et al., 2012; Mejlholm et al., 2008). An example of successful QI use is using the non-destructive technique to identify when a whole fish can be filleted with enough remaining shelf life to sell. The IFST Guidelines (IFST, 1993) defined shelf life as “the time during which the food product will: remain safe; be certain to retain desired sensory, chemical, physical and micro-biological characteristics; and comply with any label declaration of nutritional data, when stored under the recommended conditions”. As the QI score directly relates to storage time on ice, it can be used to determine the remaining shelf life of the product.

Therefore, QI is a tool that can be used at any stage of the supply chain to identify the products that need to be filleted first. For example, whole fish may only be delivered to a retail outlet once a week. If the fish with the highest QI (indicating a shorter remaining shelf life) is the first to be filleted and sold, the remaining fish can be filleted as required before the shelf life is reached. Consequently, the QI may be used instead of a best before or use-by, not determining the age of the product, but used to sell the product with the shortest shelf life first, reducing unnecessary wastage.

Although QI is a simple, quick technique to apply, the development is a lengthy process. Firstly, each species requires a separate scheme as species age differently (Boulter et al., 2009; Hyldig et al., 2012) (e.g. the texture of plaice (*Pleuronectes platessa*) does not change during storage, whereas salmon (*Salmo salar*) softens) (Hyldig et al., 2012). Secondly, QI assessors require training in the evaluation of appearance, colour, odour, and texture differences in each scheme used to standardise all results (Hyldig et al., 2012). For example, each assessor should provide the same score of texture on each sample for the QI to be useful. Therefore, there is a cost involved in developing QI schemes and training assessors to apply each scheme accurately.

Microbiological testing

Dalgaard (2000) attributed the spoilage of fresh fish fillets to microbiological activity, specifically the species *Shewanella putrefaciens* and *Pseudomonas* spp. However, the Food Standards Code only set microbiological limits for safety (FSANZ, 2014a), rather than for spoilage. Whilst there are no set limits for fresh fish, many Australian seafood companies adopt the guidelines stated by Sydney Fish Market (2013) (the largest seafood handler in Australia) (Table 2.1). Of these limits, the Standard Plate Count measures the total of organisms that grow at 30 °C, (FSANZ, 2014a). Whilst this includes some spoilage organisms (Parlapani et al., 2014), the results do not indicate those that may cause foodborne illnesses. These include *Listeria monocytogenes*, Coagulase positive *Staphylococci* and *Escherichia coli* produce toxins (Koslovac and Hawley, 2006) and *Salmonella*, (Blivet, 2000). However, as standard plate count takes up to three days for results to appear (SIA Global, 2004), the product may already be sold before results are assessed. This method is therefore used to monitor the hygiene and handling of the product within the facility such (as the effectiveness of cleaning equipment), rather than limit what is sold. Due to the safety of consumers, further research is required to determine if these limits set on the seafood industry are increasing product wastage. Therefore, as standard plate count indicates general bacteria including spoilage and food safety, it can be used as an indication of fish quality.

Table 2.1 Seafood microbiological limits set by Sydney Fish Market (2013) where CFU refers to colony forming units and MPN refers to most probable number

Test	**Limit**
Standard Plate Count	< 10^6 CFU/g
Escherichia coli	< 11/g (MPN)
Listeria monocytogenes	Not detected in 25 g
Coagulase positive Staphylococci	< 100 CFU per g
Salmonella	Not detected in 25 g

Temperature

As previously mentioned, it is important to maintain the product temperature at all times to reduce seafood spoilage (Mejlholm et al., 2012; Mejlholm et al., 2008; Olley and Ratkowsky, 1973). Software developed by Dalgaard et al. (2002) indicated the higher the storage temperature, the shorter the remaining shelf life. The Food Standards Code defines temperature control as “5 °C or below… or 60 °C or above” (FSANZ, 2014b). Therefore, by maintaining the storage temperature, the shelf life can be extended. As storage temperature influences the remaining shelf life of the product, monitoring the storage temperature and insuring the product stays cool will also minimise waste from unsold product.

Biochemical assessments

Biochemical assessments can be used to measure the breakdown that starts during rigor mortis. A high performance liquid chromatography (HPLC) test correlates the breakdown of adenosine-triphosphate (ATP) over time with the age of the fish (Özogul et al., 2000). Vázquez-Ortiz et al. (1997) combined the results from the coenzymes from this breakdown reaction to create a ‘freshness quality index’ referred to as K value. Trimethylamine (TMA) levels, the amine responsible for a “rotten fish odour” (Humbert et al., 1970) also correlated directly with sensory tests

(Krzymien and Elias, 1990) but Baixas-Nogueras et al. (2001) concluded the ratio between TMA and total volatile basic nitrogen (TVB-N) concentration, known as the P value, to be more suitable as a freshness indicator.

Texture analysis

The biochemical breakdown in the muscle can be more easily tested through texture analysis. Mechanical textural analyses can provide objective, repeatable results (Bourne, 2002). Seafood studies have shown hardness decreased over storage time (Duun and Rustad, 2008; Schubring et al., 2003), showing a relationship between mechanical results and the flesh breakdown. Texture analyses can be used to quickly determine objectively when the flesh has broken down and become mushy and unacceptable for customers, without having to undergo biochemical analyses.

Drip loss

Drip loss is a seafood quality issue of product weight loss through storage. It is measured by weighing the product over a specific time period and calculating the percentage lost. This product loss is influenced by managing the handling and storage of the product. For example, storing the fish in a slurry increased the final weight of the product by 2.5 %, whereas storing the same product on ice resulted in a 2 % weight loss over the same period of time (Erikson et al., 2011). As fish is sold by weight, this can also be an economic problem. For example, as fish is often stored in a cabinet in retail outlets, the cooling system may dry the fish, reducing the weight of the product sold. Monitoring the drip loss and making adjustments such as increasing the humidity in the storage cabinet, the fish can remain at the same temperature without losing liquid, may increase the final yield of the product (Brown et al., 2004) and thus, increase (or maintain) revenue.

Method selection

Each seafood quality method discussed covered a different aspect of the breakdown of fish over time, covering sensory, microbiological, temperature, biochemical, textural and weight changes. Any CPS implemented must not compromise on these quality aspects. However, as this project aims to model CPS development within a commercial setting, quality tests such as biochemical analyses are inaccessible to industry and are thus, not included in this project. QI, temperature and drip loss are simple tests industry can perform and microbiological tests are usually outsourced. Whilst texture analysis equipment is not readily available, results can emulate pressing a finger on fillet flesh, another simple test that can be applied within industry. Therefore, within this study, the quality index, microbiology (specifically total plate count), temperature, texture and drip loss assessments will be used to verify potential CPSs are not compromising on the product quality.

2.2.3. Combination of life cycle, economic and quality assessments

Previous research in the seafood industry has combined the use of LCA and economic opportunities (Avadí and Fréon, 2015; Parker et al., 2015; Vázquez-Rowe et al., 2011a; Vázquez-Rowe et al., 2010a), or combined the economic impact of quality maintenance (Lupin et al., 2010; Zugarramurdi et al., 2004; Zugarramurdi et al., 2007), but no research has yet compared the impact of implementing CPSs in product quality. Therefore, as CPSs may change the handling and processing of seafood products further research is required to ensure the quality is maintained or improved. This could be through monitoring temperature, microbial cross contamination, quality index, texture changes and drip loss.

2.3. Western Australian finfish supply chain

The Western Australian finfish industry produced 10,351 metric tonnes of fish compared to 8,903 metric tonnes of crustaceans and 1,092 metric tonnes of molluscs (ABARES, 2014). Most are wild caught with 9,143 metric tonnes compared to 1,208 metric tonnes of aquaculture (ABARES, 2014). Consequently, wild caught finfish have the greatest production by weight in Western Australia, thus, providing an opportunity to measure the current GHG emissions and provide targeted CPSs to mitigate the hotspots.

2.4. Potential contribution to practice

No studies to date have considered both CPSs and quality assurance for improving the environmental performance of seafood supply chain by utilising a LCA. In a commercial context the developed CPSs arising from a LCA should be combined with both an economic assessment and a quality assessment that fits the product in question. However, current published studies in the food industry do not often take this approach. For example, Pardo and Zufía (2012) used a LCA and quality assessment to recommend cleaner food processing techniques without stating the capital cost, an oversight which may influence whether the CPS is implemented. Furthermore, Pagan and Price (2008) described current CPS implementation in the food industry as “ad-hoc”, indicating further research is required into the CPS development and the impact on industry. So, CPS development in the food (and seafood) industry requires further research into the economic and quality impacts surrounding CPSs. This project aims to measure the environmental impact of fish fillets produced in the Western Australian seafood supply chain and identify and model CPSs to reduce the environmental impact with a potential long term profit and without affecting the product quality. Thus, a method in Chapter 3 has been developed to collect and analyse data to achieve this aim.

2.5. Research question definition

As the published review indicates, the seafood supply chain currently works as separate entities, and as such, most of the environmental research is in these separate entities: particularly the harvest and aquaculture stages. Therefore, there is little research highlighting where the ‘hotspots’ are within the supply chain and which stages have the greatest opportunities for CPS implementation. As a result, the research question can be asked of the Western Australian finfish supply chain:

1. What are the sources of greenhouse gas emissions in selected Western Australian finfish supply chains?

Answering this research question will combine the supply chain, to identify firstly which entity emits the most greenhouse gases, and what is causing these emissions. This then leads onto Research Question 2:

2. What CPSs are available to mitigate these greenhouse gases?

As indicated above, mitigating GHGs may affect the entity’s economic output and product quality, providing a need for Research Question 3:

3. What are the impacts of implementing these CPSs on product quality and long term costs?

In summary, this research will measure the GHG emissions from the Western Australian finfish supply chain, develop potential CPS to mitigate these emissions, and measure the impact on long term costs and product quality.

2.6. Paper 1: Environmental supply chain management in the seafood industry: past, present and future approaches

Paper 1 is a published peer reviewed journal article that addressed the cleaner production strategies applied in the various stages of the seafood supply chain and evaluated the effectiveness of the strategies implemented. The review concluded the need for collaboration in an environmental supply chain management system to ensure potential cleaner production strategies have the greatest impact.

Sustainable supply chain management in the seafood industry: past, present and future approaches

Felicity Denham, Janet Howieson, Vicky A. Solah and Wahidul Biswas

Abstract

The seafood value chain has worked separately to continually improve their processes and output to grow as businesses, resulting in any environmental sustainability measures to be minimal in the whole supply chain. Therefore, the objective of this review is to discuss the various methods used in the seafood supply chain to reduce the impacts on the environment and to provide case study examples of where such methodology has resulted in increased resource efficiency and reduction in the environmental impact.

Lessons learnt include managing the supply chain as a whole to ensure any mitigation strategies are not negated by handling further down the chain. Working as a supply chain also ensures the greatest production from the resources utilised.

To ensure the best reduction in environmental impact with the lowest costs, a supply chain management system incorporating life cycle assessment and economic modelling is recommended.

1. Introduction

In the past, the seafood value chain has worked separately to continually improve their processes and output to grow as businesses. As separate entities, each company within the value chain progresses with social, economic and environmental improvements, but only if it benefits their business directly. Jensen et al. (2010) demonstrates in a general supply chain model, collaboration with the whole supply chain increases both product quality and profit by using the same quantity of resources to meet the demand of the final product, rather than the direct customer. Thus, to continue the growth of the seafood industry, individual companies need to communicate and develop strategies with their suppliers and customers to work towards seafood sustainability.

For the purposes of this paper, the following terms are used: Sustainability is meeting "the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1988); sustainable supply chain management is working as a whole supply chain with the intention of reducing life cycle environmental impact, enhancing social equity and saving costs; cleaner production strategies are operational changes implemented by industry to reduce the impact per kg of fish while increasing eco efficiency is increasing production using fewer resources.

Sustainability takes into account environmental, economic and social objectives. These three objectives are common in different models applied to measure sustainability (Todorov and Marinova, 2011). However, the sustainability gap in fisheries need to broaden the responsibility of sustainability from an industry scale, to include suppliers, communities and non-government organisations, and a focus on carrying capacity (Standal and Utne, 2011). The definition of sustainability in fisheries should therefore include the quantity of fish harvested, atmospheric emissions and waste generation, employee safety and job security, a constant supply of fish, consistent quality of fish and the profitability of the business (Standal and Utne, 2011). In short, the responsibility belongs to all stakeholders in the seafood supply chain.

Thus, a sustainable supply chain management system is recommended to monitor and improve the sustainable development in the seafood industry. The management practice should include all stages of the supply chain, incorporating the environmental impact and covering the whole life cycle of the product (Gupta and Palsule-Desai, 2011). Supply chain collaboration also creates a competitive advantage over businesses working individually; hence improving environmental and economic performance (Cao and Zhang, 2011; Li et al., 2006). Moreover, investing in a sustainable supply chain management program presents an innovative approach to shareholders, demonstrating an availability of resources in their commitment to sustainability (Bose and Pal, 2012); thus increasing investment. By using a sustainable supply chain management tool that includes environmental, social and economic parameters, costs in energy, water and waste disposal are reduced (Bezama et al., 2012; Pagan and Prasad, 2007) and competition, investment and social wellbeing are increased. In the case of the seafood industry, limited sustainability research is available. Therefore, this paper reviews the tools, management and technologies applied across the seafood supply chain.

One management approach is developing cleaner production strategies. These may reduce the environmental impact of producing fish and fish products. van Berkel (2007) summarises cleaner production strategies into the following categories.

1. Good housekeeping
2. Input substitution: replacing resources with environmentally preferred substances
3. Technological modification: modifying existing structures to increase efficiency
4. Product modification: modifying a product to reduce material consumption and to enhance recyclability
5. Recycling waste

In referring to impact, this paper signifies the environmental impact of each stage of fish production. That is, the consequences of producing fish on the environment, which can be measured as emissions (such as carbon dioxide), solid waste, energy consumption and resource efficiency. For industry to be resource efficient, they need to use the least amount of consumables to produce the largest quantity of fish.

2. Scope of the review

This paper reviews the environmental and economic aspects of sustainability in seafood; that is, the efficient and economic use of resources for fish harvesting, processing and marketing. The social aspect of sustainable seafood is covered in Coulthard et al. (2011) and Moore et al. (2013) and is therefore excluded from this review. Applying cleaner production strategies is one of the potential pathways to attain improved economic and environmental objectives of seafood sustainability.

Prior literature reviews in global seafood industries and the management of the industry (twenty-five reviews from 2001) do not assess sustainability as defined through the entire supply chain. Instead they refer to specifics such as by-catch (Bellido et al., 2011; Catchpole and Gray, 2010), wild caught harvest (Crowder et al., 2008), fisheries and aquaculture management (Bjørndal et al., 2004; Caddy and Cochrane, 2001) and the difference between them (Pelletier et al., 2007), fish waste

(Ferraro et al., 2010; Gehring et al., 2011; Jayasinghe and Hawboldt, 2012; Kim and Mendis, 2006) including wastewater (Chowdhury et al., 2010; Kitis, 2004; Leitão et al., 2006; Terada et al., 2011), feed production (Cho and Bureau, 2001) (Francis et al., 2001; Tacon and Metian, 2009; Torrissen et al., 2011), farming (Gamborg and Sandøe, 2005; Gauthier and Rhodes, 2009; Lima dos Santos and Howgate, 2011; Naylor and Burke, 2005; Partridge et al., 2008; Weir et al., 2012), and the application of the life cycle assessment tool in seafood (Vázquez-Rowe et al., 2012a). Only one review (Crowder et al., 2008) covers the environmental impact and cleaner production strategies of the entire supply chain. However, this review omits the implications of an economic analysis therefore providing no sustainable supply chain incentives to industry.

The objective of this review is to discuss the various methods used in the seafood supply chain to reduce the impacts on the environment and to provide case study examples of where such methodology has resulted in increased resource efficiency and reduction in the environmental impact.

3. Methods

Tables 1 and 2 list the papers reviewed on cleaner production tools applied to improve the impact within the seafood supply chain. Papers reported on tools to measure the environmental impact of the seafood industry (measuring energy and water consumption, recording food miles and applying the life cycle assessment tool) and cleaner production strategies implemented or suggested to improve the environmental impact. All strategies were classified into general strategies (Table 1) and specific strategies (Table 2). General strategies can be applied to any supply chain stage and include product quality monitoring, waste product recycling, modification of equipment and technology and reduction of storage space required and specific strategies from each stage in the supply chain include harvest, transport, processing and packaging, storage, retail and the whole supply chain.

4. Tools for assessing environmental impact within the seafood supply chain

Methods for assessing the environmental impact within the seafood supply chain have been developed and applied: these include measuring energy and water consumption, measuring ‘food miles’ and using life cycle assessment.

4.1 Measuring energy and water consumption

Some companies pay their bills without taking note of their energy and water consumption. By monitoring consumption over time using the bills as they arrive, these resources can be reduced.

Research into harvesting methods in wild caught fisheries found strategies to reduce diesel use. For example, Wakeford (2010) performed audits on fishing vessels including the method and type of harvest and the fuel consumed. Marriott et al. (2011) has also analysed energy consumption by interviewing skippers, using their experience of various boating equipment and the effect it had on their energy efficiency. Although Marriott et al. (2011) included a larger quantity of vessels in their analysis than Wakeford (2010) (thirty six and six vessels respectively), the data collected was based on the skipper's opinion of the techniques used rather than a repeatable measure such as vessel audits against a set standard (Wakeford, 2010). Therefore, auditing vessels and measuring the exact energy consumption provides solid data monitored over time while interviews have a narrow scope.

Energy and water consumption is also measured in processing facilities. Firstly, Bezama et al. (2012) and Pagan and Prasad (2007) successfully involved processors to monitor and reduce their energy consumption using cleaner production agreements – in this case, a set of specific opportunities to reduce the environmental impact were documented, signed by volunteer processors and the progress monitored by internal (Pagan and Prasad, 2007) and external (Bezama et al., 2012) audits. The agreement written with each participant, outlined specific objectives including reduction of waste and wastewater, reduction of water, energy and coolant consumption (Bezama et al., 2012). Pagan and Prasad (2007) focussed on reducing water and energy consumption, reducing and reusing waste and wastewater, recycling and reducing packaging and minimising cleaning agents use without compromising on quality. Both Bezama et al. (2012) and Pagan and Prasad (2007) attribute their programs' success to each participating firm's involvement in monitoring their energy and water consumption.

4.2 Measuring food miles

Another method of measuring the environmental impact is recording “food miles” (tonnes of food multiplied by km travelled, represented as tkm). Research by Coley (2011) and Kissinger (2012) calculated the carbon dioxide emitted from food travel by recording the transport method, the quantity taken and the distance travelled, resulting in a calculation of the quantity of carbon dioxide emitted per tkm. Identifying the global greenhouse gas emissions may provide enough evidence to include food transport in food policies instead of a separate transportation policy (Kissinger, 2012).

4.3 Life Cycle Assessment

Life cycle assessment (LCA) is the most widely used method for measuring the environmental impact. A LCA evaluates the product throughout its lifespan to determine the possible ecological consequences (International Organisation for Standardization, 2006). The method provides results in many formats including the global warming potential (the quantity of greenhouse gases or carbon dioxide equivalents), acidification potential (sulphur dioxide equivalents) and eutrophication potential (nitrate equivalents) (Hall, 2011) per functional unit. The functional unit is a reference unit according to the process analysed (International Organisation for Standardization, 2006) for example, a 400 g package of frozen cod fillets (Ziegler et al., 2003).

LCA can also validate the impact of potential mitigation strategies. Thrane et al. (2009) provided recommendations to two industries and followed up on their progress six years later, determining the change of the environmental impact over time. As trialling strategies to determine their environmental impact is an accurate method of justifying recommendations, it is not necessarily practical. Other researchers have tested strategies concurrently (Claussen et al., 2011; Eide et al., 2003; Pardo and Zufía, 2012; Thomassen et al., 2008; Vázquez-Rowe et al., 2010), compared results with similar literature (Iribarren et al., 2010; Jørgen Hanssen, 1998), or modelled the strategies (Hospido and Tyedmers, 2005; Hospido et al., 2006; Renouf et al., 2011).Whilst comparing strategies concurrently provides reliable results, it involves either using current methods, or implementing changes without validation. Therefore, LCA saves both time and money by validating strategies and demonstrating the impact to industry before implementation.

In summary, measuring energy consumption, food miles and using LCA as strategies to reduce the environmental impact are used in all stages of the seafood supply chain. Whilst there are different operations for each stage, they will all consume power, transport products, and be able to calculate the emission factor of each process using LCA.

5. Overall environmental strategies for improving seafood supply chain management

The tools used to measure the environmental impact of the seafood industry identified areas of potential change, resulting in the need for strategies to reduce the identified impacts. Generic strategies used throughout the supply chain include monitoring the product quality, recycling waste products, modifying the current equipment and reducing the storage space required.

5.1 Product quality monitoring

Monitoring the product quality can be a strategy to reduce the environmental impact. By implementing a quality assurance system such as HACCP (Hazard Analysis and Critical Control Points, a quality control system used to identify and prevent chemical, biological and physical contamination in the food industry) in a processing environment, regular product monitoring will result in a higher quality product and fewer rejected products, thus reducing both product and resource wastage (Lupin et al., 2010). In all stages of the supply chain, poor quality raw materials increases labour costs due to product rejection or reprocessing to meet specifications. Therefore, by managing the product quality from the beginning, the quantity of rejects can be reduced, resulting in a higher yield and reduced waste and thus, a higher efficiency of resources utilisation (Zugarramurdi et al., 2004; Zugarramurdi et al., 2007). Reducing fish wastage mitigates methane and carbon dioxide emissions released in the anaerobic digestion process (Hall, 2011) (breakdown process of fish fat, protein and carbohydrates, eventually resulting in methane, carbon dioxide and hydrogen gas emission).

Drip loss (moisture leakage of fish over time) waste can also be reduced and the final yield increased by managing the handling and storage of the product. There are several different methods of reducing the drip loss including storing the fish in a slurry and increasing humidity in the cabinet or storage area. By using a slurry the fish does not dry out, but absorbed 2.5 % weight in four days in comparison to losing 2 % when stored in ice for the equivalent time (Erikson et al., 2011). Thus, the environmental impact will reduce per kg if the product gains weight over time in an ice slurry. However, fish is often stored in a cabinet when on display for customers where the cooling system dries the fish. By increasing the humidity in the storage cabinet, the fish can remain at the same temperature without losing liquid, thus increasing the final yield (Brown et al., 2004). Either way, the storage method of the product will influence the loss over time, increasing the relative environmental impact.

Managing the quality of seafood and reducing the waste is difficult, as the seafood expiry date is set according to the age of the product, not taking into account storage temperature and initial bacterial count. Therefore, a model for dynamic expiry dates including storage conditions and bacterial counts can estimate the losses and reduce losses from 17.13 % to 3.79 % (Tromp et al., 2012). Freezing reduces wastage if fish sales are unlikely before the dynamic expiry date (Thrane et al., 2009). Although freezing requires energy and refrigerants, adding to the environmental impact (e.g. ozone layer depletion) it also increases the percentage of sellable product, providing revenue from fish which would otherwise cost in wastage (Thrane et al., 2009). Losses are reduced by managing the quality.

5.2 Waste product recycling

Another way seafood industries are reducing their waste is by creating by-products from waste materials, thus increasing resource efficiency and profits. Processing by-products can be used for fish feed (Gunasekera et al., 2002), bait (Svanes et al., 2011), pet food (Thrane et al., 2009), liquid fertiliser (Dao and Kim, 2011) and a source of lactic acid for plastic production (Gao et al., 2006). Edible products including fish sauce (Shih et al., 2003), fish oil (Garcia-Sanda et al., 2003; Thrane et al., 2009; Wu and Bechtel, 2008) and calcium (Iribarren et al., 2010) are also produced from processing fish waste.

5.3 Modification of equipment and technology

Slight operational modifications to existing capital equipment can contribute to the environmental impact.

The refrigerant used makes a difference in the global warming potential and ozone layer depletion over time. Blowers and Lownsbury (2010) tested three different refrigerants for a 10 t freezer and found the chlorofluorocarbon gas R-12 released less carbon dioxide equivalents than the hydrofluorocarbon R-134a and the hydrofluoroether HFE-143 m. Therefore, modifying the refrigerant required impacts the emissions released. Svanes et al. (2011) and Winther et al. (2009) also found replacing the refrigerator lowered leakage of the refrigeration gas reducing wastage and thus, ozone layer destruction. For example, a refrigerator leaked 19.2 % on the boat resulted in recommendations to change the coolants used to R22 or R404a to reduce the greenhouse gases emitted (Vázquez-Rowe et al., 2013).

Specific boat modifications lead to increased efficiency. Ziegler and Hansson (2003) found modifying the tackle reduced fuel consumption. Wakeford (2010) recommended using a bulbous bulb on the bow, increasing the length of the vessel and using an asymmetric rudder to increase fuel efficiency. Sterling and Goldworthy (2007) discussed alternative energy sources to diesel, including biodiesel, but found all had a low energy density that is not suited to power boats. Instead, Sterling and Goldworthy (2007) recommended choosing the type of engine required to the purpose as slow speed engines use less diesel than high speed.

Resource efficiency including energy and refrigerants are also increased by maintaining and upgrading equipment.

5.4 Reduction of storage space required

Storage space can be used more efficiently, particularly in a refrigerator, freezer or on ice, thus reducing the energy and refrigerants required. Edible fish portion space is created by removing heads and tails (Claussen et al., 2011; Thrane et al., 2009). Retaining the waste for further processing (such as creating by-products) then ensures reusable products are not lost in storage (Thrane et al., 2009).

Maintaining quality, recycling waste, improving equipment and reducing the storage space required are strategies recommended for the entire seafood supply chain. However, additional strategies may be advised for specific supply chain activities.

6. Sectoral cleaner production strategies of the seafood supply chain

The seafood supply chain consists of harvest (wild caught or aquaculture), transport, processing and packaging, storage and retail. The following summarises specific cleaner production strategies for each supply chain stage.

6.1 Harvest

Aquaculture, farming of aquatic organisms such as fish, molluscs, crustacean and plants (Jerbi et al., 2012) involves many activities that potentially cause environmental impacts including feed production, breeding, fish growth and harvest. Specific aquaculture environmental impact strategies have been developed for farm management, fish effluent and feed production.

Fish effluent builds up under the cage over time, instead of dispersing in the ocean, increasing biochemical oxygen demand. Research into cleaning the water identified fish and plankton as able to remove the discharge between shrimp harvests (McKinnon et al., 2002). Nevertheless, not all species are successful in cleaning the ocean, as fish effluent stunted mussel growth (Cheshuk et al., 2003).

A major part of aquaculture is the production of dry feed. Researchers agree feed production has the biggest environmental impact on farming (Aubin et al., 2009; Boissy et al., 2011; Jerbi et al., 2012; Pelletier et al., 2009; Winther et al., 2009) with LCA studies demonstrating up to 90 % of all energy use in aquaculture is from producing feed (Pelletier et al., 2009). However, it is difficult to quantify the hotspots of feed production as there is no breakdown of published analyses (Aubin et al., 2009; Bosma et al., 2011; Parker and Tyedmers, 2012; Pelletier et al., 2011). Yet, the predominant environmental issues are generally the energy consumption, the ingredients used and the feed quantity required per kilogram of fish.

One reason for the high impact of feed is associated with the harvesting of the fish used for feed. For example, krill harvested in Antarctica required transportation to shore in its natural form, using diesel in boat fuel, before drying into feed (Parker and Tyedmers, 2012). Increasing the harvest size per trip (Parker and Tyedmers, 2012) and reducing fuel consumption by 40 % during harvest (Ziegler and Hansson, 2003) were shown to improve energy efficiency, implementing the “good housekeeping” cleaner production strategy.

Different ingredients in fish feed have different environmental impacts such as carbon dioxide released. The fish's level in the food chain influences the emissions as carnivores release nitrogen and phosphorous wastes (Aubin et al., 2009) from high protein diet. Therefore, Ellingsen and Aanondsen (2006) recommend vegetarian diets as they have a lower environmental impact. Yet, a vegetarian diet is not necessarily as efficient, as it reduces the growth rate, the feed intake, the energy productive value and the lipid intake of the fish after 85 days (Espe et al., 2006). The fish fed on soy resulted in different colour and texture to the control fish (Kaushik et al., 1995). In contrast, Glencross et al. (2012a; 2012b) argues that digestion of a vegetarian diet depends on both the species of fish and the polysaccharide used. Consequently, the diet of fish can influence the environmental outcome (a product modification cleaner production strategy), but still requires further investigation.

Wild caught fish harvested from their natural habitat have a different environmental impact to aquaculture fish. Vázquez-Rowe et al. (2011) found the harvest had the highest impact of the seafood supply chain. Consequently, it is important to plan the harvest method and monitor the by-catch to ensure the highest efficiency of resources.

Wild caught harvest methods vary in their costs and quantities. For example, although trawling harvests a larger quantity of fish than long lining and gill net methods (Ziegler and Hansson, 2003), it consumes more fuel. Consequently, comparative analyses imply trawl harvests are expensive per kilogram of fish (Utne, 2008). Utne (2008) argues that operations between harvest methods are so different, environmental impacts cannot be compared per kilogram of product. Nevertheless, as both methods are able to capture the same species, the various results of different harvest methods show the efficiency of resources and their effect on the environment per kilogram of product.

By-catch is the term used for fish discarded at sea and is an important efficiency measure. There are several reasons for discarding fish at sea: they are undersized, they are not a species that sells well or the operation has met its' quota and wants to keep the species that bring a larger profit. Bellido et al. (2011) recommends four points to reduce the fish by-catch; understand the quantity of fish available and work with it, improve selective processes to catch targeted fish (a "technology modification" cleaner production strategy), develop tools for management decisions using the ecosystem so the land can be read by non-scientists and finally, let the public get involved to engage industry to improving their practices.

6.2 Transport

Transporting fish between stages of the supply chain is an important process. However, its environmental impact is minor compared to harvest (Andersen, 2002; Weber and Matthews, 2008) and is difficult to measure as it depends on production and distribution costs (Tlusty and Lagueux, 2009). Therefore, it is important to classify the mode of transport and the impact of processing when developing cleaner production strategies.

The method of transport affects the environmental impact (Coley et al., 2011). Travel by ship has a low impact, but requires the product to be frozen due to the length of transport time (Tlusty and Lagueux, 2009) in order to maintain quality. For a frozen product, ship has been shown to have the lowest environmental impact, followed by truck and then air freight (Vázquez-Rowe et al., 2012b). Also, to deliver fresh fish from Norway to East Asia and United States of America via truck and aeroplane required ten times the energy required to transport frozen fish by truck and ship (Andersen, 2002).

The method of transport and thus, the environmental impact depends on the processing techniques used. Due to the refrigeration energy consumption and costs, Andersen (2002) recommends processing such as drying, smoking or freezing before exporting out of the continent (Bezama et al., 2012). Therefore, it no longer needs overnight delivery, instead using alternative transport methods like ship or trucks thus, reducing the energy used in transportation (Andersen, 2002).

Kissinger (2012) suggests three steps to reduce the carbon dioxide emissions from food transport. Firstly, start recording the distances the food travels, secondly, let consumers know the impact the travel is having on the environment and finally to increase the efficiency of the transport methods used.

6.3 Packaging and processing

The method of packaging fish differs according to purpose, thus, incorporating different environmental impacts. The packaging system used is influenced by the final market (Sanyé et al., 2012) and assists in reducing drip loss by restraining the fluid retention in the fillet (Williams and Wikström, 2011). Although processing and packaging requires energy, Williams and Wikström (2011) justify a 20 % energy increase if it is associated with different packaging techniques that maintain the final weight of fish. If shelf life extension is needed, Pardo and Zufía (2012) recommend modified atmosphere packaging (often referred to as MAP, modified atmosphere packaging involves gas flushing the product, usually with carbon dioxide to increase shelf life) as energy, heat and power are significantly less than thermal pasteurisation and high pressure processing. If an extended shelf life is not required, packaging in plastic bags is a better alternative as fewer resources by weight are required (Hospido et al., 2006). Depending on the purpose of the product, a packaging method can be designed to reduce the environmental impact, applying the "product modification" cleaner production strategy.

6.4 Storage

The storage of fish causes potential environmental impacts such as global warming, ozone depletion and solid waste. Fish can be frozen, refrigerated, kept on ice or super chilled (frozen at -2 °C). Choosing the storage method early in the supply chain preserves energy.

Super chilling reduces the temperature of the fish or fillet to -1 to -4 ° C, reducing the need for ice (Claussen et al., 2011) and slowing biochemical changes, without causing the structural changes of freezing (Gallart-Jornet et al., 2007). By reducing the ageing process, super chilling for nine days gave the equivalent quality of a fish stored on ice for two days (Gallart-Jornet et al., 2007) but did not differ in quality after four days with fish stored on ice (Erikson et al., 2011). An LCA study found super chilling uses less power than freezing and ice production (Winther et al., 2009), is therefore more efficient and therefore a "technological modification" cleaner production strategy.

Freezing fish also does not require ice, thus increasing the quantity of product to fit in same space (Winther et al., 2009). However, freezing the product and keeping it frozen throughout its life cycle, uses similar energy consumption to ice production (Winther et al., 2009), thus creating similar emissions.

Storing fish in a slurry, even after the initial cooling, improves the quality of the final product. The slurry did not affect the rigor process or the texture, but gave a significantly better quality index, regardless of initial cooling method (Erikson et al., 2011). The slurry also reflected ideal temperature control on the day ten microbiological count with the slurried fish total plate count of 2.4 $x10^4$ CFU/g compared to 4.3 x 10^6 CFU/g (Erikson et al., 2011).

6.5 Retail

Once the fish has arrived in the retail outlet, it is stored in a refrigerated display cabinet until sale, when it is packaged for the consumer. Consequently, the product temperature and the final packaging influence the environmental impact.

One strategy in retail is to maintain the product temperature in the display cabinet. Opening the display cabinet doors continually throughout the day leads to temperature changes affecting the quality of the fish. Therefore, Laguerre et al. (2012) recommends using an air curtain to retain the cabinet temperature when the door is open. An air curtain is a stream of chilled air streaming down the entrance to the cabinet, providing a barrier and preventing outside heat entering the cabinet (James and James, 2002). Hence, temperature can be maintained throughout without the cabinet straining, conserving energy.

Another strategy in retail outlets is to use packaging resources efficiently. In a standard shopping basket, the local market had a higher plastic bag consumption per sale than the hypermarket (supermarket combined with a department store) (Sanyé et al., 2012). However, the hypermarket was found to use packaging as a marketing tool and used 2.5 times the weight of the local market's plastic bag consumption (Sanyé et al., 2012). Therefore, retail outlets are prone to over package, causing wastage. Planning packaging systems using minimum resources reduced wastage and thus, the environmental impact.

Between the energy consumption in retail outlets and the packaging, there is a lot of wastage in the retail business. Consequently, quantifying resources consumed using

LCA, will identify areas of environmental impact and direct cleaner production strategy development.

7. Whole supply chain assessment and management

A whole of chain approach is important in an environmental sustainable supply chain management system to ensure eco-efficiency. Information from the entire chain provides precise data identifying economic and environmental improvement opportunities (Erol et al., 2011). A review by Wognum et al. (2011) agrees that mitigation strategies used in one stage of the supply chain results in costs filtering through to subsequent partners. Thus, the succeeding facilities have the power to undo the sustainable practices as well as finance the cost of the strategy. Clift and Wright (2000) concurs, demonstrating the majority of environmental opportunities are from the primary resource extractor (the harvesters and aquaculture facilities), but there is no economic benefit from implementing cleaner production strategies. Instead, any profits from these strategies are received downstream. Therefore, to reduce the environmental burden on the primary producers, Clift and Wright (2000) recommend recycling resources. For example, if the harvest of fish has the highest environmental impact, the responsibility of reducing the impact also falls to the processor and retailer to recycle waste products, ensuring resource efficiency.

Lozano (2007) applied the Nash equilibrium theory to sustainability, suggesting each chain participant makes the best decision, according to decisions of every participant. Thus, without a supply chain management tool, each firm makes decisions according to their suppliers and customers. If one company chooses to use sustainable practices, then it will ignore the benefits associated with the participation of industries in the supply chain both up and down-streams. Thus, environmental and efficiency measures are more successful when supply chains collaborate. Cooperation throughout the chain is vital not only to get the greatest profit from the least amount of resources, but also providing access to sustainable opportunities that may otherwise go unnoticed.

To have an effective supply chain partnership that reduces environmental impact requires planning from the whole chain. Firstly, the strategies within the supply chain must benefit every partner involved and support each sector’s corporate strategies to ensure and maintain interest and support (Walker, 2012). Secondly, to keep the strategies effective and evolving, the communication within the chain needs to increase (Walker, 2012). With effective communication and aligned goals, the seafood industry can create a supply chain management plan to increase resource efficiency.

General supply chain models are available, but few are specific to fisheries. For example, working as a general whole supply chain has been modelled to create competitive advantage (Li et al., 2006), have better decision making (Lozano, 2007), lead to increased investment (Bose and Pal, 2012; Erol et al., 2011) and profit (Singer and Donoso, 2008), improve exports (Costantini and Mazzanti, 2012) increase social acceptability (Costantini and Mazzanti, 2012) and increase efficiency (Cao and Zhang, 2011). Increasing efficiency will reduce costs, and resources will produce a larger quantity of output, which will reduce the environmental impact per kg of fish.

An economic analysis is vital to prove to firms that implementing changes to ensure an environmentally sustainable business is financially viable so industries are urged to apply strategies. The goal of such cleaner production strategies is to attain both economic and environmental benefits, thus protecting each company's profits. The model by Nath et al. (2011) determined the cost benefits from mitigation strategies before implementation to identify the economic feasibility. The model includes a series of spreadsheets, calculating the costs, income and profit of the product measured from each stage to enhance the economic efficiency of the supply chain. An alternative economic tool, life cycle cost, calculates the cost of acquisition, ownership and disposal of a product over a defined period of its life cycle. When used in a Norwegian fishing fleet, the life cycle costing broke costs into capital costs influenced by equipment condition, operational costs influenced by fuel efficiency, environmental costs including the cost of waste, low quality products and by-catch and maintenance costs including breakdowns and waste disposal (Utne, 2009). By doing this, areas of greatest expense and resource inefficiency can be identified, and the costs of potential strategies can be modelled.

8. Lessons learnt and the way forward

Despite the studies in each sector of the seafood supply chain, there are still areas that require further work and strategy implementation.

8.1 Tools for assessing environmental impact within the seafood supply chain

Notwithstanding the ease and practicality of in-house environmental assessments such as measuring energy and water consumption, they are limited in the results provided. Accounting only for energy consumption in the direct processes of the seafood industry ignores the energy and resources required to produce all other materials required in the process. Energy and water assessments are also limited to one stage of the supply chain and are therefore restricted in measuring the full efficiency of the industry. Instead, incorporating energy and water consumption with all inputs such as the LCA, identifies the areas that consume the most energy and water and strategies developed ensures the largest production from the least amount of resources.

Focussing only on the travel distances and transport mode using food miles does not account for impacts of processing, harvesting and retail. Although measuring the impact of transport on the environment is useful, neither Coley (2011) nor Kissinger (2012) assesses the prominent impacts of production and "hotspots". If a product has a high impact in transport (for example, travelled from overseas), it does not necessarily account for the impact from processing and transport combined (Coley et al., 2011). Instead, combining both processing and transport data provides a clearer picture. Coley (2011) highlights sustainable practices such as food miles should not be isolated but instead combine with economic, social and broader environmental measures. The LCA tool is an example that includes all aspects of the supply chain and incorporates well with economic analyses including the life cycle cost tool.

LCA's have been widely used in wild caught (Ellingsen and Aanondsen, 2006; Thrane, 2006; Vázquez-Rowe et al., 2010, 2011; Vázquez-Rowe et al., 2012b; Ziegler and Hansson, 2003; Ziegler et al., 2003) and aquaculture facilities (Ellingsen and Aanondsen, 2006; Jerbi et al., 2012; Pelletier et al., 2009; Tlusty and Lagueux, 2009), but research is lacking in entire seafood supply chains. One reason for this is the reluctance of partners to participate in whole of chain studies as it appears difficult and expensive to industry (Walker et al., 2008). Therefore, both the environmental and economic benefits of supply chain collaboration need to be demonstrated through a proven theoretical framework.

8.2 Overall environmental strategies for improving seafood supply chain management

Unlike processing and retail outlets, there is no compulsory quality system for aquaculture and wild harvest of seafood. Although some wild caught harvest facilities use quality index (Lawler, 2003) there is not the incentive worldwide as in the processing and retailers. By monitoring the quality, suppliers will develop shelf life and product consistency, and reduce wastage. Furthermore, a quality product can command a higher price and results in a satisfied customer.

As recycling waste products of any kind takes financial and time investment into new processes, there is little incentive to initiate. Industry is concerned at getting their own product on the market as quickly as possible, rather than develop products that may not initially create a significant profit. Thus, for those industries that do not have recycling methods in place, there is a need for research in start-up costs, methodology and economic output.

Equipment used in the seafood industry is diverse and all have different environmental impacts. Currently, a Standard Australia (2000) audit conducted by Wakeford (2010) measures the efficiency of each piece of equipment. Consequently, it is expensive and inefficient use of resources to analyse each piece of machinery individually. Hence, there is a need to create a model or checklist to simplify machinery audit process, enabling supply chain members to assess their technology.

Currently, when fish travels from the boat to a processing facility, both edible and inedible portions take up space in the transport vehicle. Once filleted, only the usable portion of fish is transported, increasing the quantity of product in the space provided and thus, reducing the quantity of transport fuel and the cost of transport. Therefore, depending on the final use, removing inedible portions such as the head and tail will provide more space for the sellable product.

In contrast, ice reduces the holding capacity of fish. If fish is already below five degrees (as it should be from cooling immediately after harvest through to consumption), then refrigeration is enough to maintain the temperature. Ice is only required in cooling fish or when refrigeration is unavailable (e.g. in delivery vans). By reducing the ice, more fish can fit in the available space.

8.3 Sectoral cleaner production strategies of the seafood supply chain

Studies in aquaculture do not agree on the nutritional composition of the feed (Glencross et al., 2012a; Glencross et al., 2012b), particularly as some prefer vegetarian feeds (Ellingsen and Aanondsen, 2006) to meat feeds (Espe et al., 2006; Kaushik et al., 1995). Therefore, there is a need to standardise feed and the nutritional value needed for each stage of the food chain. In other words, standardise the main ingredients, allowing for modification of protein content depending on the species.

There is also very little knowledge of the environmental impact of breeding and growth of the fish. Available literature is on the feed ingredients and quantity and the quality of the final product.

When looking at wild caught harvest, each boat varies due to construction and harvest method, resulting in a large difference in the energy efficiency of harvest methods. The differences also make it difficult to apply general methods to reduce by catch.

The transport of seafood cannot be isolated from the supply chain. As fish has a limited shelf life, the mode of transport (particularly long distance) depends on the processing methods to ensure the product is in an edible state on arrival. Thus, the method and distances travelled are important considerations in a supply chain capacity.

Again, the packaging and processing of the product depends on the final purpose. Therefore, the most efficient methods occur when the supply chain communicates their needs effectively in a sustainable supply chain management system.

Although the length of time fish is stored depends on the fish shelf life and demand, the energy and refrigerants required for long-term storage can be both expensive and environmentally damaging. Thus, a generic model applied to frozen and super chilled products demonstrating both the emission factor and the resource cost of storage over time is required.

Seafood supply chain studies ignore retail outlets’ significance as they compose a minimal percentage of the total environmental damage. However, Styles (2012) demonstrates the necessity of including retailers to push for eco-efficient products. Retailers also use the influence of customers to rally for sustainable products (Styles et al., 2012).

8.4 Whole supply chain management

To consider environmental supply chain management in seafood, all sections of the supply chain need to work together to create economically viable strategies. Although Winther et al. (2009) and Ellingsen et al. (2009) covered harvest and production, neither followed through to retail nor covered the economic implications of strategies recommended. LCA's have also been applied to harvest, transport and processing only to assess environmental impacts, but no literature has been found on retail stage, or the economic aspects of possible mitigation strategies. Thus, the combination of LCA and economic tools is useful to determine the feasibility of each mitigation strategy, but until now has not been achieved.

Industry needs to be convinced of the economic benefits of supply chain management including profits and competitive advantages (Soosay et al., 2012) using an economic analysis. Walker (2012) suggests educating consumers to purchase from sustainable supply chains will also encourage industry sustainability. Using both economic modelling and consumer pressure can influence industry to improve their efficiency and environmental impact using sustainable supply chain management practises.

In conclusion, there are many methods of measuring the environmental impact of the seafood supply chain. Nevertheless, as separate strategies within each supply chain stage, the outcomes are minimal. Therefore, to ensure the best reduction in environmental impact with the lowest costs, a sustainable whole of supply chain management system is recommended.

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Tables

Table 1 List of general cleaner production strategies applied or recommended in the seafood supply chain

Type of Cleaner Production Strategy	Strategy	Reference
Product Quality Monitoring		
Good housekeeping	Quality control costs reduced over time using HACCP	Lupin et al. (2010)
Good housekeeping	Quality of raw materials influences labour and costs	Zugarramurdi et al. (2004)
Good housekeeping	As quality increases, failure therefore cost decreases	Zugarramurdi et al. (2007)
Good housekeeping	Maintaining humidity during retail display prevents drip loss	Brown et al. (2004).
Good housekeeping	Ice slurry storage improved quality, microbiology and reduced drip loss	Erikson et al. (2011)
Good housekeeping	Expiry date management, promotes sales before aging defects occur	Tromp et al. (2012)
Good housekeeping	Freezing reduced aging of unsold fish	Thrane et al. (2009)
Waste product recycling		
Recycling waste	Fish waste used for feed	Gunasekera et al. (2002)
Recycling waste	Fish waste used as bait	Svanes et al. (2011)
Recycling waste	Fish waste used for pet food	Thrane et al. (2009)
Recycling waste	Fish waste used for liquid fertiliser	Dao and Kim (2011)
Recycling waste	Fish waste fermented for the production of biodegradable plastics	Gao et al. (2006)
Recycling waste	Fish waste used for fish sauce	Shih et al. (2003)
Recycling waste	Oil extracted from wastewater after canning fish	Garcia-Sanda et al. (2003)
Recycling waste	Oil is extracted from wastewater after canning fish	Thrane et al. (2009)
Recycling waste	Oil extracted from pink salmon heads and viscera	Wu and Bechtel (2008)
Recycling waste	Calcium extracted from mussel shells	Iribarren et al. (2010)
Modification of Equipment		
Input substitution	Choice of refrigerants influences the global warming potential.	Blowers and Lownsbury (2010)
Technology modification/ good housekeeping	Refrigerator maintenance reduced leakage of the refrigeration gas	Svanes et al. (2011)
Technology modification	Underperforming refrigerator replacement reduced leakage of the refrigeration gases including chlorofluorocarbons	Winther et al. (2009)
Technology modification	Boat structural changes increased energy efficiency	Ziegler and Hansson (2003)
Technology modification	Boat structural changes increased energy efficiency in wild harvest	Wakeford (2010)
Technology modification	Boat engine choice increased energy efficiency	Sterling and Goldworthy (2007)
Reduction of storage space		
Product modification	Space is increased for the edible portion of the fish by removal of heads and tails.	Claussen et al. (2011)
Product modification	Space is increased for the edible portion of the fish by removal of heads and tails.	Thrane et al. (2009)

Table 2 List of specific cleaner production strategies applied or recommended in the seafood supply chain

Type of Cleaner Production Strategy	Strategy	Reference
Aquaculture production		
Good housekeeping	Fish and plankton cleaned water after farming shrimp	McKinnon et al. (2002)
Good housekeeping	Increased krill harvest (per trip) used in feed production reduced impact of fish feed	Parker and Tyedmers (2012)
Technology modification	Using a boat fuel efficiency reduced impact of fish feed	
Input Substitution	Using plant resources instead of protein for feed production	Ellingsen and Aanondsen (2006)
Wild caught harvest		
Technology modification	Improve selective processes to catch targeted fish and reduce catch up unwanted species by modifying fishing gear	Bellido et al. (2011)
	Develop tools for management decisions using the ecosystem so the land can be read by non-scientists	
	Involve the public to pressure industry into improving their processes	
Transport		
	Pressure industries into choosing local products by regulate travel distances of product	Kissinger (2012)
Good housekeeping	Inform about distances food travels to influence shopping habits towards environmentally	
Technology modification	Increase fuel efficient transport by promoting train travel over truck	
Technology modification	Mode of transport is as important in emissions released as distance travelled	Coley et al. (2011)
Technology modification	Ship freight has a lower carbon footprint than air and truck freight	Tlusty and Lagueux (2009)
Technology modification	Ship freight has the lowest carbon footprint impact, followed by truck and then air freight	Vázquez-Rowe et al. (2012b)
Good housekeeping	Process fish before transporting to reduce product weight, space required and refrigeration	Andersen (2002)
Good housekeeping	Process fish before transporting to reduce product weight, space required and refrigeration	Bezama et al. (2012)
Processing and Packaging		
Good housekeeping	Packaging prevented drip loss of fillets	Williams and Wikström (2011)
Product modification	Modified atmosphere packaging used less power than thermal pasteurisation and high pressure processing	Pardo and Zufía (2012)
Input substitution	Used plastic bags instead of tinplate cans to reduce weight of the packaging wastage	Hospido et al. (2006)
Storage		
Good housekeeping	Super chilling fish increases volume on truck as ice is not needed	Claussen et al. (2011)
Good housekeeping	Super chilling slows aging without freezing	Gallart-Jornet et al. (2007)
Good housekeeping	Super chilling uses less power than freezing and ice production	Winther et al. (2009)
Retail		
Technology modification	An air curtain maintains temperature of display cabinet where fish fillets are stored during retail opening hours	Laguerre et al. (2012)
Technology modification	An air curtain maintains temperature of display cabinet where fish fillets are stored during retail opening hours	James and James (2002)

CHAPTER 3. Methods

3.1. Introduction

This chapter covers the methods applied to achieve objectives one and two (Figure 1.1). These were:

1. Identify the areas of greatest greenhouse gas emissions from selected Western Australian seafood supply chains
2. Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs

The research was split into two parts based on the objectives. Firstly the greenhouse gases (GHG) emitted in the Western Australian finfish supply chain was measured using a partial life cycle assessment (PLCA) to identify the process or input causing the most emissions (Objective 1). Following these results, potential cleaner production strategies (CPSs) were developed from the areas of greatest GHG emissions within the supply chains measured (Objective 2). Any potential CPSs in the seafood industry requires consideration of costs and product quality as previously described in Chapter 2 (cost and quality methods used in this study are further described in sections 3.6.2 and 3.6.3). Methods are described under the following sections:

- Description of the finfish supply chain as a pre-requisite for conducting a partial life cycle assessment analysis and to identify direct and indirect stakeholders
- Partial life cycle assessment following ISO 14040-44 applied in identifying the hotspots in the Western Australian finfish supply chain (Results presented in Chapter 4)
- Development and selection of potential CPSs (Results presented in Chapter 5)
- Assessment or evaluation of selected CPSs (Chapter 5) using:
  - Partial life cycle assessment
  - Economic assessment
  - Quality assessment

3.2. Selection of finfish supply chains in the study

The process in environmental supply chain management requires all stakeholders in a supply chain to work together to measure the impact and identify strategies to attain economically viable outcomes with low GHG emissions (Gupta and Palsule-Desai, 2011) (Chapter 2: Paper 1). Thus a combination of the Western Australian seafood supply chain stages' GHG emissions, provides a more effective picture of environmental supply chain management.

3.3. Description of finfish supply chains in the study

Three different supply chains were measured in this study (Figure 3.1 and Table 3.1) made up of the one harvest method, two processing facilities and three retailers.

Table 3.1 Summary of study supply chains

Regional supply chain	Independent supply chain	Major supply chain
Harvest	Harvest	Harvest
Regional processor	Independent retailer	City processor
Regional retailer		Supermarket

The city processor and supermarket did not provide supplier locations for transport data. Consequently, transport was excluded when comparisons between the supply chain and stages occurred. Transport was included in the Regional and Independent supply chains.

The consumption stage was not included in this study as fish can be consumed in many different ways. For example, the fish may be frozen and defrosted, pan fried, barbequed, slow cooked, steamed, or baked. Consumers may also flavour, marinate, or use in a stew. As there are many different methods of cooking fish filets, studying the consumption stage would induce too many variables and is beyond the scope of this research.

Furthermore, this research is built on as a research study aiming to provide potential CPS to assist the seafood industry to reduce their GHG emissions. As the Australian government is working specifically with industry to reduce GHG emissions (Commonwealth of Australia, 2015), rather than the general public, this project aims to measure the GHG emissions from the industry sector of the finfish supply chain.

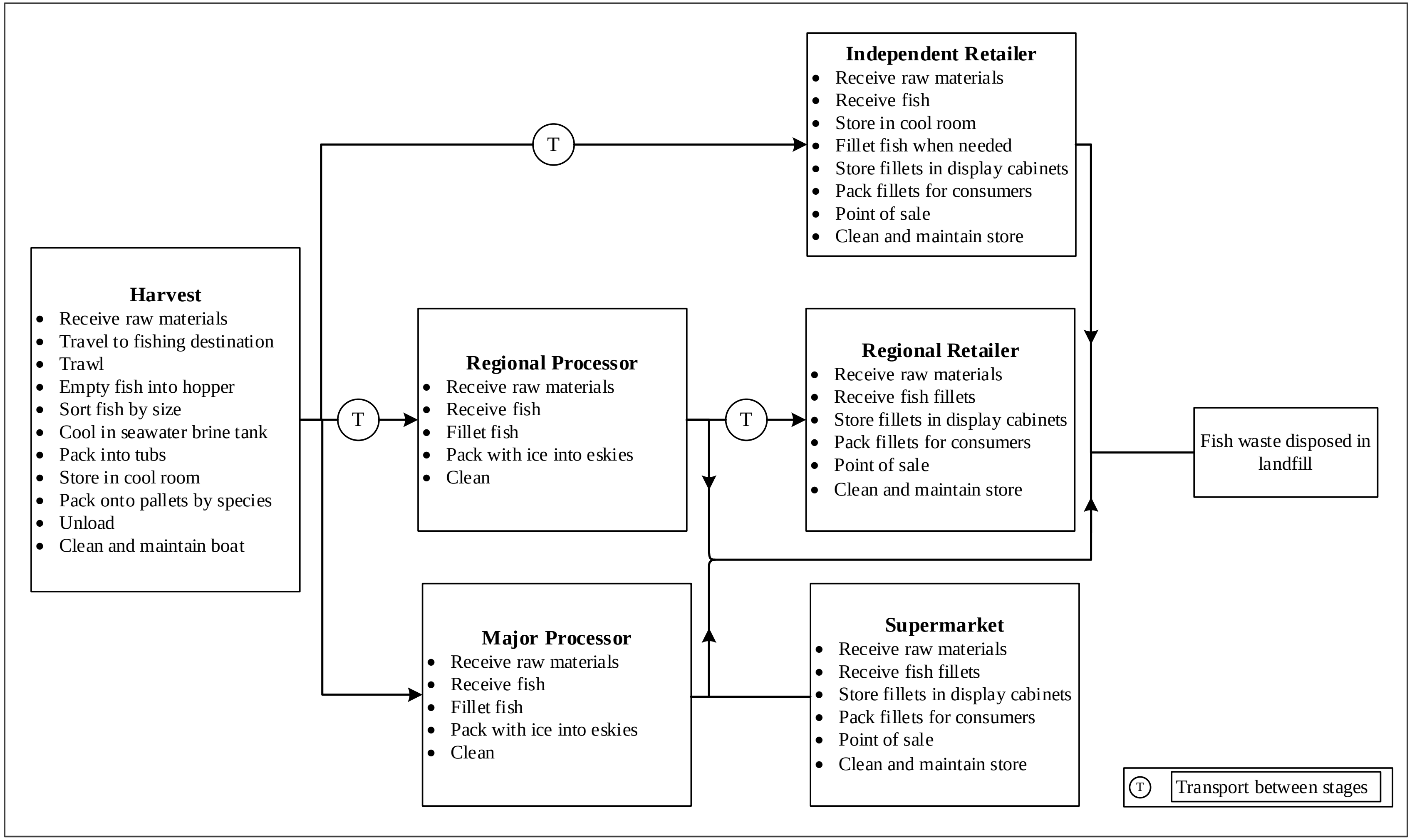

Figure 3.1 Supply chain diagram of firms in study

3.3.1. Harvest

A trawl harvest company was selected as trawling catches the largest quantity of finfish in Western Australia (ABARES, 2014). The trawl harvest occurred in the North Coast Bioregion as described by the Department of Fisheries (2014). The vessel travelled approximately 200 km from Exmouth port before trawling started. The trawl method involves spreading a large net out the back of the boat and pulling it in the opposite direction the target school of fish is swimming. The net spans about 20 m wide and is pulled in, where the fish is emptied into a hopper. The post-trawl fish process included, sorting the fish by size and species into baskets (or polypropylene bags for large fish), cooling in seawater brine for four hours and packing into tubs for cool room storage once the internal temperature reached 0 °C. This process continued from day 2-9 at sea (Figure 3.2). Once the vessel arrived back at port after ten days at sea, the fish were packed onto pallets by species and unloaded off the vessel, onto a refrigerated truck. The vessel underwent cleaning and maintenance before it returned to sea.

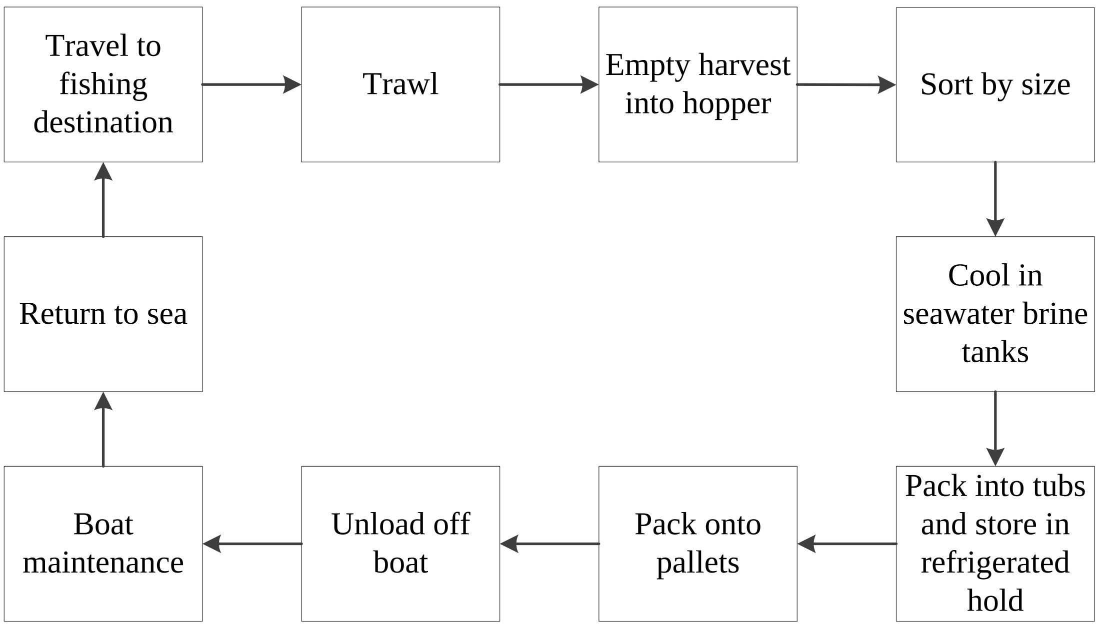

Figure 3.2 Process on the trawl vessel

This harvest process included a vessel powered by diesel. The diesel is used for running the vessel, and subsequent systems (GPS, sonar systems, engine etc.), the trawling process of dragging a net behind the vessel, cooling the brine water to bring the fish down to 0 °C and the refrigerator the fish is stored in until unload.

The selected trawl firm provides 20.5 % of the finfish harvested from the North Coast Bioregion (Department of Fisheries, 2012). 73 % of the finfish caught in this bioregion was using the trawl method described above (Department of Fisheries, 2012). The harvested species in this region differ from other regions in Western Australia, as the large coastline results in varying water temperatures throughout Western Australia. Whilst the dominant species in the bioregion where the harvest process took place were Crimson snapper (*Lutjanus erythropterus*), Bluespotted emperor (*Lethrinus* sp.) and Rosy threadfin bream (*Nemipterus furcosus*), species were located and caught in this bioregion according to demand. Forty different species were caught by this company and species were separated and sold off to different entities. For example, species such as Red emperor (*Lutjanus sebae*) supplied restaurants and Saddletail Snapper supplied retail outlets. The dominant species caught by this particular company Crimson snapper and Bluespotted emperor. Therefore, this study is representative of firms dealing with species including (but not restricted to) these species.

3.3.2. Processing

Once on land, the fish was transported to a processing facility. Two different processing facilities were assessed in this study: the Regional Processor in the Regional Supply Chain and the City Processor in the Major Supply Chain. Processing finfish included transport of the fish to the processing facility, filleting by hand, disposing of the head, frames, tail and guts, packaging (depending on the processor) and storing the fillets.

The small regional processor was located 3.7 km from the landing port in Exmouth. This processor filleted and packaged fish for a wholesale market (into polystyrene eskies), delivering fillets to surrounding restaurants and the small regional retailer. Saddletail and Crimson snappers (*Lutjanus malabaricus* and *Lutjanus erythropterus* respectively) were the dominant species processed in this facility, selected from the harvest stage as the product most likely to sell as a fillet. Whilst these were not necessarily the dominant species of the harvest stage, they were the species sold specifically as fillets to retail outlets rather than whole fish.

The city processor, located in Perth, 2,000 km from the landing port, filleted, vacuum packaged and froze fillets for retail market. A small retail outlet was located onsite, but not included in this study.

3.3.3. Retailing

Retailing finfish in this study included transport of the fish to the retail facility, storing fillets in a cool room, displaying fillets in a cabinet for customers and packaging when sold. This study did not include the sale of whole fish

The small regional retailer was located in Exmouth, 1.6 km away from the regional processor. The fillets were stored in the display cabinet under polyvinyl chloride (PVC) and wrapped in low-density polyethylene (LDPE) bags, kraft paper and a paper bag when sold.

The independent retailer was located in Perth, 1,269 km away from the landing port. The fish were stored in a cool room and filleted as required, bypassing a separate processing facility. Once filleted, they were stored in the display cabinet during opening hours under PVC and placed in the cool room overnight. When sold, the fillets were wrapped in LDPE bags, paper and singlet high-density polyethylene (HDPE) shopping bags.

The supermarket stored fillets in display cabinet during the day and cool room overnight. When sold, the fillets were wrapped in LDPE bags, paper and singlet HDPE shopping bags.

As the processing and retail facilities handled products other than fish (prawn and other shellfish in all processing and retail facilities and game products in the city processor), the inputs were separated by the percentage of fish products by weight in the facility. The inputs allocated included power, water and refrigeration gases as data provided was per facility.

3.4. Data collection

Ethics approval for this project was obtained from Curtin University’s ethics committee prior to data collection (approval numbers RD-47-10 and SPH-23-2014) (Appendix 1). To fulfil the ethics approval, each participant was given an information sheet with the project details and signed a consent form (Appendix 1).

Collaborating firm interviews occurred between August 2012 and September 2013 and were compiled into an Excel spreadsheet. Primary harvest data included the quantity of fish harvested, diesel and vessel maintenance required per year. Primary processing and retail data included the quantity of fish purchased, fish waste, electricity and water consumption, consumable items and the distances all travelled to the site.

Secondary data included different data sources: international literature provided data estimation that was not possible to collect on the field (i.e. refrigeration gas leakage); medical safety data sheets for chemical quantities; and international databases to calculate the life cycle inventory (LCI) data for background processes (i.e. packaging materials, gloves, chemicals, vessel maintenance, and paper).

Recruitment of a city processor and retailer was difficult. After collecting the primary data from a supermarket, the company withdrew from the study. The final supermarket used was contacted by email and for confidentiality reasons did not provide the name or location of the store assessed. Two seafood processors were also interested in the study and provided verbal commitment, but did not find the time for an interview, delaying the study. The final processor provided the majority of the data within an hour interview.

3.5. Partial life cycle assessment

PLCA is the most widely used method for measuring the environmental impact, in this case, GHG emissions. PLCA evaluates the product throughout its lifespan to determine the possible ecological consequences (International Organisation for Standardization, 2006). This study applies a partial approach as it did not take into account upstream activities such as fish consumption as described above (Barton et al., 2014). This PLCA approach follows the four steps of ISO 14040-44 (International Organisation for Standardization, 2006) goal, life cycle inventory, impact assessment and interpretation (Figure 3.3). Results from this section are presented in Chapter 4.

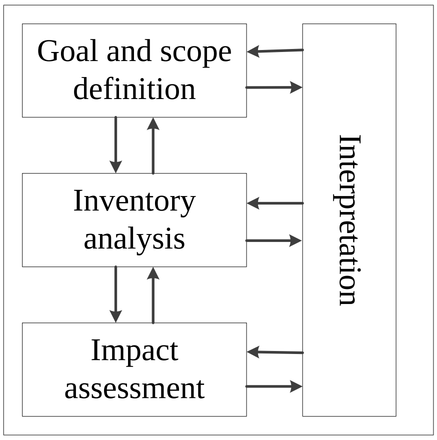

Figure 3.3 Four steps of PLCA (International Organisation for Standardization, 2006)

3.5.1. Goal and scope

The goal and scope provide the backbone for the PLCA process by defining and describing the product assessed, identifying the purpose of the study, and defining the system boundaries and functional unit (International Organisation for Standardization, 2006). The functional unit which is required to ascertain the goal of LCA, is a reference unit according to the process analysed (International Organisation for Standardization, 2006), and in food studies is defined either by weight, nutritional composition, land area utilised or economic value (Roy et al., 2009). The functional unit in fact defines the system boundaries which refer to what stages of life cycle are included in the study. As the product is sold as fillets in the retail outlets, one metric tonne of fish fillets was used as the functional unit in this study.

The goal was to ascertain and compare the GHG emissions from three Western Australian finfish supply chains. The system boundaries of this section included harvesting, processing and retailing of fish fillets, waste disposal and the production and transport of the items purchased (Figure 3.1, Tables 3.3-3.7), but excluded the cooking and consumption stages of the supply chain and all downstream activities, including food service and restaurant sectors and handling after the product left the retail facility.

Like Finkbeiner et al. (2011) and Engelbrecht et al. (2013), this research considered carbon footprints in terms of an LCA, with the focus on one impact category – the global warming impact, through GHG emissions.

Table 3.2 System boundaries of the harvest stage

Inputs	Harvest	Outputs
Consumable Items • Carton liners • Detergent • Grease • Hydraulic oil • Lanolin grease • Pallet wrap • Polypropylene bags • Rope • Rust rinse • Tubs *Energy* • Diesel *Transport*	1. Travel to fishing destination 2. Trawl 3. Empty fish into hopper 4. Sort by size and species 5. Cool in brine tank 6. Pack onto pallets 7. Store in cool room 8. Unload off boat onto truck 9. Boat maintenance	• Whole fish to: – Regional Processor – Independent Retailer – City Processor • GHG emissions • Refrigerant leakage

Table 3.3 System boundaries from the Regional Processor

Inputs	Regional Processor	Outputs
• Whole fish from Harvest *Consumable Items* • Carton liners • Detergent • Disposable gloves • Eskies • Hand sanitiser • Ice • Paper towels • Water *Energy* • Batteries • Diesel *Transport*	1. Receive fish and consumable items 2. Fillet fish 3. Pack fillets into eskies with ice 4. Store in cool room until required 5. Clean	• Fillets to Regional Retailer • Fish waste • Refrigerant leakage • GHG emissions

Table 3.4 System boundaries from the Regional Retailer

Inputs	Regional Retailer	Outputs
• Fish fillets from Regional Processor *Consumable Items* • Detergent • Disposable gloves • Eskies • Fillet covers • Hand sanitiser • Hand soap • Paper bags • Paper wrapping • Plastic bag for fillet • Water *Transport*	1. Receive raw materials and fish fillets 2. Store fillets in display cabinets 3. Pack fillets for consumers 4. Point of sale 5. Clean and maintain store	• Fillets to Consumers • Refrigerant leakage • GHG emissions

Table 3.5 System boundaries from the Independent Retailer

Inputs	Independent Retailer	Outputs
• Whole fish from Harvest *Consumable Items* • Detergent • Disposable gloves • Fillet covers • Hand sanitiser • Hand soap • Paper towels • Paper wrapping • Plastic bag for fillet • Plastic checkout bags • Water *Transport*	1. City Retailer 2. Receive raw materials 3. Receive fish 4. Store in cool room 5. Fillet fish when needed 6. Store fillets in display cabinets 7. Pack fillets for consumers 8. Point of sale 9. Clean and maintain store	• Fillets to consumers • Fish waste • Refrigerant leakage • GHG emissions

Table 3.6 System boundaries from the City Processor

Inputs	City Processor	Outputs
• Whole fish from Harvest *Consumable Items* • Bleach • Boxes • Carton liners • Degreaser • Disposable gloves • Eskies • Hairnets • Hand sanitiser • Hand Soap • Pallet wrap • Vacuum bags • Water	1. Receive raw materials and fish 2. Fillet fish 3. Pack with ice into eskies 4. Store in cool room until needed 5. Clean	• Fillets to Supermarket • Fish waste • Refrigerant leakage • GHG emissions

Table 3.7 System boundaries from the Supermarket

Inputs	Supermarket	Outputs
• Fish fillets from City Processor *Consumable Items* • Bench Spray • Degreaser • Detergent • Disposable gloves • Hand sanitiser • Hand Soap • Paper towels • Paper wrapping • Plastic bag for fillet • Water	1. Receive raw materials and fish 2. Receive fish fillets 3. Store fillets in display cabinets 4. Pack fillets for consumers 5. Point of sale 6. Clean and maintain store	• Fillets to consumers • Fish waste • Refrigerant leakage • GHG emissions

3.5.2. Life cycle inventory

The life cycle inventory (LCI) considers all the relevant inputs and outputs for processes that occur during the life cycle of a product within the system boundaries applied. This included both site specific data collected from industry interviews, and literature, reports and medical safety data sheets to provide data estimation from elements that were not possible to collect on the field.

Industry interviews included (but were not restricted to):

- Identifying the processes in each supply chain stage (Section 3.3)
- Calculating the inputs and outputs for the functional unit
    - For example, the supermarket used 5 cartons of gloves a week, totalling 260 per year. One carton of gloves weigh 0.8 kg, therefore, 208 kg of gloves used per year. As 13 % of sales were fish, that comes to 27.04 kg of gloves per year. 140 metric tonnes of fillets were sold in a year, making 0.193 kg of gloves used per metric tonne of fish fillets,
- Quantifying total production of fish fillets and other products
    - For example, of all products in facility, 50 % were fish fillets, 40 % prawns and other seafood and 10 % game meat,
- Quantifying all consumable items, energy, water, and their costs
    - For example, Spent $ 830 over 48 days, averaging $ 6,311.46 per year. From the Horizon Power (2012) prices including supply charge, first 1,650 kwh per day and more than 1,650 kWh per day, this came to an average of 195,900 kWh per year. As fish was only 50 % of this processor, that accounted to 97,950 kWh per year. When divided by the total 120.9 metric tonnes of fish fillets per year, each metric tonne of fish fillets required 8.099 kWh.
- Quantifying fish waste
    - For example, the filleting yield was 45 %, therefore, 1,264 kg per metric tonnes of fish fillets was discarded to landfill,
- Listing all machinery and quantifying their use
    - For example, refrigerator and how much is for fish compared to other seafood products

- Listing all maintenance of machinery and the consumable items required
    - For example, the quantity of refrigerant required to keep the refrigerators and display cabinets running
- Listing all methods of transport to next chain partners including quantities, frequency and mode of transport
    - For example, the paper to wrap purchase was manufactured in Melbourne. It travelled 3,411 km by articulated truck to a Perth depot. It then travelled 1,231 km in an articulated truck to the company's storage unit. When required, a light commercial vehicle travelled 22 km to pick up the paper rolls.

A pre-structured questionnaire was developed to gather information on inputs and outputs of life cycle stages by interviewing stakeholders in the finfish supply chain. Full questionnaires are shown in Appendix 2.

The LCI from the current Western Australian finfish industry included the quantities, ingredients and transport distances of all the materials and energy consumed in the harvest, processing and retailing of fish fillets, and the quantity of all outputs such as waste and refrigeration leakages within the system boundaries stipulated. Inputs and outputs were categorised into consumable items, energy and outputs (Table 3.8).

Although tubs were intended to be reused, they are not always returned to the harvest stage. Therefore, the results in this study show the tubs purchased on a yearly basis, not the total quantity of tubs used. Eskies were purchased as single use items as their brittle nature results in breakages during unpacking.

The refrigerant emission used in this study was from leakage that occurs during general use and maintenance. Estimated leakage rates were taken from The Australian Institute of Refrigeration (2012)

Table 3.8 Categories of inputs and outputs for different stages in the LCI

Harvest	Processors	Retailers
Consumable Items		
• Carton liners • Detergent • Grease • Hydraulic oil • Lanolin grease • Pallet wrap • Polypropylene bags • Rope • Rust rinse • Thick gloves • Tubs	• Boxes • Carton liners • Degreaser • Detergent • Disposable gloves • Esky • Hairnets • Hand sanitiser • Hand soap • Ice • Pallet wrap • Paper towels • Water	• Bench spray • Checkout paper bags • Checkout plastic bags • Detergent • Disposable gloves • Esky • Fillet covers • Hand sanitiser • Hand soap • Paper to wrap purchase • Paper towels • Plastic bag for fillet • Water
Energy		
• Diesel (vessel power)	• Batteries (scales) • Electricity (refrigeration)	• Electricity (refrigeration and scales)
Outputs		
• R404a refrigerant	• R404a refrigerant • Fish waste	• R404a refrigerant • Fish waste

3.5.3. Impact assessment

The impact assessment evaluates the environmental impacts based on the inventory analysis.

The input and output data in the LCI was entered into the Simapro 7.33 (PRé Consultants, 2013) life cycle assessment (LCA) software to ascertain the GHG emissions associated with the production of one metric tonne of fish fillets. Firstly, all inputs and outputs were divided into their ingredients if possible (e.g. which chemicals were in the detergent used). Secondly, the input and output data from the LCI were attached to the relevant emission databases or libraries in Simapro or its libraries (PRé Consultants, 2013). The library in the LCA software is a database, which consists of units of energy consumption, emissions factors and materials data for the production of one unit of a product (Biswas et al., 2008). The units of input and output data from the LCI depend on the units of the relevant materials (for example kg, L, kWh) in Simapro or in the libraries. All libraries used were Australian so as to keep emission factors local to represent local situation and to find more realistic carbon footprint values. In the absence of Australian databases in the software, databases were created by using energy and material information from locally published reports and literature (Table 3.9).

Table 3.9 Existing and newly developed emission factor libraries

Libraries sourced from Simapro databases	**Libraries developed**
• Articulated truck	• Batteries
• Diesel	• Ice
• Electricity	• Fish waste disposal in landfill
• Carton liners	• Bench spray (cleaning item)
• Checkout paper bags	• Boxes
• Checkout plastic bags	• Drain cleaner
• Grease	• Detergent
• Hairnets	• Degreaser
• Hydraulic oil	• Disposable gloves
• Pallet wrap	• Esky
• Paper to wrap purchase	• Fillet covers
• Paper towels	• Hairnets
• Plastic bag for fillet	• Hand sanitiser
• Polypropylene bags	• Hand soap
• Rope	• Lanolin grease
• Water	• R404a refrigeration gas
	• Rust rinse

	• Thick gloves • Tubs • Vacuum bags

PLCA provides results in many different environmental impact categories (referred to as characterisation) including the global warming potential (the quantity of greenhouse gases or carbon dioxide equivalents), acidification potential (sulphur dioxide equivalents) and eutrophication potential (nitrate equivalents) (Hall, 2011a). This study is a limited focussed LCA as it only deals with the greenhouse gas emissions including carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) gases in the form of carbon dioxide equivalent (CO_2 –eq), emitted from the production, transportation and use of inputs in all life cycle stages (Finkbeiner et al., 2011). The CO_2 –eq was calculated by multiplying the N_2O and CH_4 emissions (e in Equation 3.1) in the LCI by 298 and 25 respectively and adding the CO_2 emissions according to IPCC's fourth assessment report (Forster et al., 2007).

$$\mathrm{CO_2\text{-}eq} = \mathrm{CO_2}e + 298 \times \mathrm{NO_2}e + 25 \times \mathrm{CH_4}e \tag{3.1}$$

3.5.4. Interpretation

The final phase of PLCA included a) identification of the environmentally significant issues and the causes of each hotspot by revisiting the LCI and identifying the inputs, outputs and processes responsible for each hotspot that helps discern relevant cleaner production or mitigation strategies; b) evaluation of study completeness, sensitivity and consistency; and c) conclusions and recommendations for reducing the GHG emissions from the supply chains measured (International Organisation for Standardization, 2006).

Specifically, this involves ranking the individual input and output CO_2 –eq results within each supply chain and each supply chain sector. The categories discussed in Section 3.5.3 (consumable items energy, storage and waste) in each supply chain and supply chain sector were also ranked by GHG emissions. The areas with the highest GHG emissions (referred to as hotspots) were then used to develop CPSs (Section 3.6).

Final recommendations were made according to CPS analysis including PLCA, economic assessment and quality assessment discussed in Section 3.6.

3.5.5. Uncertainly analysis

Monte Carlo analysis has been used to track and measure the propagation of uncertainty in LCA results of this current research. The Monte Carlo analysis has been performed by running repeated assessments using random input values chosen from a specified probable range. The effect of this input uncertainty can then be measured by variability of the assessment output (Lo et al., 2005).

The mean, standard deviation and standard error of the mean from each supply chain and individual stages was calculated using the Monte Carlo Simulation (1,000 runs, 95 % confidence interval) using Simapro 7.33 (PRé Consultants, 2013). From these figures, the standard deviation was calculated as a percentage of the mean, and the percentage differences calculated from Equation 3.2. A significant difference was determined if the standard deviation percentage was higher than the percentage difference between samples.

$$\text{Percentage difference (\%)} = \frac{\text{mean}_a - \text{mean}_b}{\text{mean}_b} \times 100 \tag{3.2}$$

Where mean_a and mean_b refer to the two supply chains or supply chain stages in the comparison (in kg of CO_2 –eq).

3.6. Cleaner production strategies

From the LCA results of the supply chain study, potential CPSs were developed under the categories discussed by UNEP (2002) and van Berkel (2007). Examples of some of these prevention practices to reduce undesirable impacts are listed under these categories:

- good housekeeping – to improve operation, maintenance and management procedures (e.g. maintaining refrigerators);
- input substitution - the use of environmentally preferred and ‘fit-for-purpose’ process inputs (e.g. fish packaging);
- technology modification – improve the production facility (e.g. biogas plant for generating electricity from fish waste to substitute carbon intensive grid electricity);

- product modification – change product features to reduce its lifecycle environmental impacts (e.g. selling product as a whole fish instead of fillets); and
- re-use and recycling – on site recovery and re-use of materials, energy and water (e.g. reuse of plastic or polyethylene terephthalate).

These were then assessed as feasibility of implementation, the impact on consumers and the impact on the respective companies. Then, selected CPSs were assessed for their potential GHG reduction (Section 3.6.1), current economic viability (Section 3.6.2) and impact on product quality (Section 3.6.3). These tests were to ensure implementation of any CPS would potentially reduce the GHG emissions per metric tonne of fish fillets, have a potential long term profit whilst maintaining (or improving) the current the quality of the fish fillets as discussed in Chapter 2. Results from this section are presented in Chapter 5.

3.6.1. Partial life cycle assessment using revised life cycle inventory

PLCA was applied again as mentioned above after incorporating CPSs. Here the goal was to compare the GHG emissions from each CPS scenario with the current systems per metric tonne of fillets. This determined the GHG saving potential of different alternative CPSs to treat the hotspot(s).

A system expansion approach was taken to any new products developed from the CPSs assessed. The GHG emissions from the equivalent product on the market (if applicable) were included separately in the input and output tables as a displaced product, with negative emissions (reducing what is already on the market). Results of these displaced products were graphed as a negative value to show the difference between the inputs and outputs of the CPS, and the product displacement GHG emissions.

3.6.2. Economic assessment

An economic assessment has been carried out to determine the most profitable CPS with the highest CO_2 mitigation potential for a particular hotspot. Hence, the potential costs and profits of alternative CPSs for treating particular hotspot have been determined in the relevant supply chain stage. Two economic analyses were applied in this study: the quantity of GHG mitigated per $ 1 of investment on the

CPS and; a cost benefit analysis to determine the long term costs and profits of each CPS.

The first analysis is to compare the total costs to the potential GHG reduction from the CPS (Equation 3.3). Results indicate the CPS that reduces the most GHG for the lowest cost i.e. this method determines the cheapest (short term) solution for reducing the most GHG emissions. These results were compared by graph.

$$\text{kg of CO}_2\text{ –eq per \$} = \frac{\text{Quantity of fillets sold} \times (\text{total GHG} - \text{total GHG with CPS})}{\text{Total capital investment}} \tag{3.3}$$

The cost benefit analysis method utilised was based on the methods described in Ridge Partners (2014). Net Present Value (NPV), the value of an investment over a certain time period in the current value of money was calculated for the comparison (Equation 3.4). Results indicate the long term investment value of each CPS, taking into account potential revenue over a fifteen year period.

$$\text{NPV} = \sum_{t=0}^{H} \frac{B_t - C_t}{(1+i)^t} \tag{3.4}$$

Where:

- H = project horizon years. A 15 year investment horizon has been assumed for this cost-benefit analysis to measure the costs and revenue of each investment, taking into account capital depreciation over time as described by Ridge Partners (2014). This time period was chosen to reflect the lifespan of capital equipment included in this study (such as refrigerators with an average lifespan of 14 years in 2005 (Bakker et al., 2014))
- t = Time (years)
- B_t = Total financial benefits from fish production in the year ‘t’. Benefits are any potential revenue in $ such as increased yield, leading to increased income.
- C_t = Total costs of finfish production in the year ‘t’
- i = discount rate set at 6 % (Department of Treasury, 2013)

- An inflation rate of 2.5 % per annum for all estimated costs and benefits of fish production according to the RBA's aim of 2-3 % (Reserve Bank of Australia, 2014).
- Maintenance costs of the fish waste biogas system included an additional 10 % of the total capital cost each year

The costs collected were capital costs, fixed operating and maintenance costs and potential benefits and were collected from interviews, literature and industry quotes. The benefits were potential revenue including cost reductions from implementing the CPS (e.g. energy costs no longer required as the CPS increased energy efficiency). All costs and benefits were calculated per year. Results were then graphed to show the CPS with the greatest potential return on investment.

3.6.3. Quality assessment

The impact of the potential CPSs on finfish fillet quality was tested (as appropriate) to determine any potential issues that may affect the product quality, and thus, reduce the value of the product. As fillets were stored in the processing facility for up to three days, any potential CPS that affect the handling of the fillets themselves were monitored for storage temperature, drip loss, quality index, microbiology and texture. Saddletail snapper (*Lutjanus malabaricus*) fillets were used as an example in this study as it had the highest volume from the regional processor.

The fresh fillets were purchased from a local processor, packaged as per normal production (unless impacted by the selected CPS) and stored in an industrial sized refrigerator for three days. Fillets were tested before and after the storage time for texture, drip loss, quality index, microbiology and texture.

Temperature

Thermocron temperature loggers purchased from OnSolution (Baulkham Hills, NSW, Australia) were used to monitor the temperature inside the cartons tested and between fillets. The temperature loggers had a resolution of 0.5 °C, measurement range of -30 to 85 °C and an accuracy of 1 °C. Temperature loggers were read using eTemperature software provided by OnSolution (Baulkham Hills, NSW, Australia). Loggers were set to record the temperature between fillets every five minutes.

Drip loss

Fillets were weighed immediately after filleting and again after the storage time to determine any moisture lost in storage (Equation 3.5).

$$\text{Drip loss (\%)} = \frac{\text{Fillet weight after filleting} - \text{Fillet weight after storage}}{\text{Fillet weight after filleting}} \times 100 \qquad (3.5)$$

Quality index

A quality index (QI) is a “recognised readily understandable, rapid, practical, yet scientifically based” (Boulter et al., 2009) method of grading the quality of a product (in this case, fish) (described in Chapter 2). The scheme works by scoring the fish fillet according to the scheme (in this case, the scheme is presented in Table 3.13) which correlates to equivalent storage days in perfect condition i.e. ice. The lower the score, the higher the remaining shelf life as further described in Boulter et al. (2009). The quality parameters of the fillets were recorded immediately after filleting and again after the CPS stimulation according to the scheme in Table 3.13. This scheme was validated in Section 3.6.4.

Microbiology

The total aerobic count of the fillets was measured immediately after filleting and again after the CPS stimulation. Three fillets from day zero and two fillets from each carton on day three were submitted to a commercial testing company and analysed for total aerobic count according to the Australian Standards AS 5013.1-2004 (SIA Global, 2004) and AS 5013.5-2004 (SIA Global, 2005) methods.

Texture

Texture was measured using the TA.XT2*i* Texture Analyser set up using a 25 kg load cell and a rectangular probe (3cm by 2 cm). The pre-test speed was 2 mm/second, and the test speed was 0.8 mm/second. The probe compressed 50 % of the fillet and held it in place for one minute.

Four fillets immediately after filleting and again after the CPS stimulation were cut to the probe size from the sections marked in Figure 3.4.

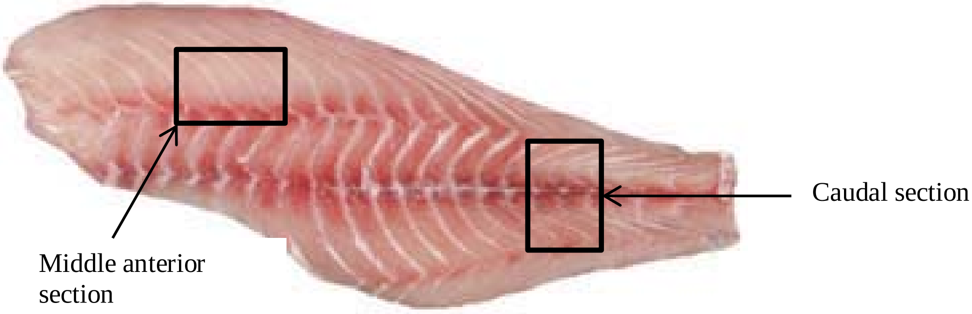

Figure 3.4 Areas of fillet tested for texture (CSIRO Marine and Atmospheric Research)

The TA.XT2*i* Texture Analyser produced a graph of the force taken to compress the fillet over one minute. From the data collected, the hardness and springiness were determined using the Texture Exceed Expert (TEE) software. The software measured the maximum force to compress the fillet and the force after holding for one minute.

3.6.4. Quality index validation

The quality index described in Section 3.6.3 was validated for use in CPS development.

Methods

Raw Saddletail snapper (*Lutjanus malabaricus*) fillets were purchased from a fish retailer. The fish were trawl harvested, stored whole in a slurry and filleted when required. At the laboratory, the fillets were stored at 2 degrees covered in LDPE plastic. Samples were stored for 0, 2, 4, 6 and 8 days with slight variation due to fillet availability.

A preliminary QIM scheme (Table 3.10) was developed by two people recording changes in the fillets from filleting to spoilage. The parameters were scored from 0-3 according to spoilage.

At least six panellists trained participated in two training sessions. Raw Saddletail snapper fillets of different storage time were placed on the stainless steel bench at room temperature. Panellists were given examples of each parameter in the scheme in the training sessions and each fillet was labelled with its age. In each session, panellists were asked to rate each fillet using the developed scheme. During the training sessions, the scheme was modified as per the suggestions of the panel. In the following validation sessions the fillets were only labelled by three-digit numbers and were evaluated according to the final scheme.

Table 3.10 Preliminary Saddletail snapper fillet quality index

Parameter		Score
Texture	Skin bounces back	0
	Finger mark remains	1
	Mushy	2
Blood	Pink	0
	Orange	1
	Brown	2
Odour	Fresh seaweed/seawater	0
	Metallic	1
	Sour	2
Colour	Creamy pink/bright sheen	0
	Dull pink	1
	Brown tinge	2
Transparency	Transparent	0
	Opaque	1
Gaping	None	0
	Slight gaping	1
	Gaping everywhere	2
	Quality Index	**11**

The Torry scheme was used to evaluate raw Saddletail snapper fillets without skin in three sessions. Six trained panellists assessed 15 fillets during the experiment; three fillets per storage day (0, 2, 4, 6 and 8 days with slight variation due to fillet availability), coded with three-digit numbers without information about the storage time.

Samples weighing 10–15 g were taken from the loin part of the fillets and placed on a plate coded with three-digit random numbers. The samples were cooked on high for 30 seconds in a microwave.

The panel observed the odour and flavour of the fillets and matched them to the Torry Scheme for Medium Cooked fish (Table 3.11). The panel evaluated the cooked samples, coded with three-digit numbers without information about the storage time, using the list developed during training. Each sample was evaluated in triplicate over the three sampling days.

Table 3.11 Torry Scheme for medium cooked fillets

Odour	**Score**
Initially weak odour of boiled cod liver, fresh oil, starchy	10
Shellfish, seaweed, boiled meat, oil, cod liver	9
Loss of odour, neutral odour	8
Wood shavings, wood sap, vanillin	7
Condensed milk, boiled potato	6
Milk jug odours, reminiscent boiled clothes	5
Lactic acid, sour milk, TMA	4
Lower fatty acids (e.g. acetic or butyric acids), decomposed grass, soapy, turnipy, tallow	3
Flavour	**Score**
Boiled cod liver, watery, metallic	10
Oily, boiled cod liver, sweet, meaty characteristic	9
Sweet and characteristic flavours, but reduced in intensity	8
Neutral	7
Insipid	6
Slight sourness, trace of “off” flavours, rancid	5
Slight bitterness, sour, “off” flavours, TMA, rancid	4
Strong bitterness, rubber, slight sulphide, rancid	3

Results

From the scores measured, the relationship between quality index and age of fillet provided an R value of 0.78 ($p < 0.001$) (Figure 3.5). To increase the strength of this relationship, the parameters were assessed separately to determine the most useful for this species (Table 3.12).

As texture and gaping had an R value of > 0.5 and p value of < 0.05, they were excluded from the scheme. These results indicated the panel were unable to distinguish differences in texture and gaping between different ages of fillets.

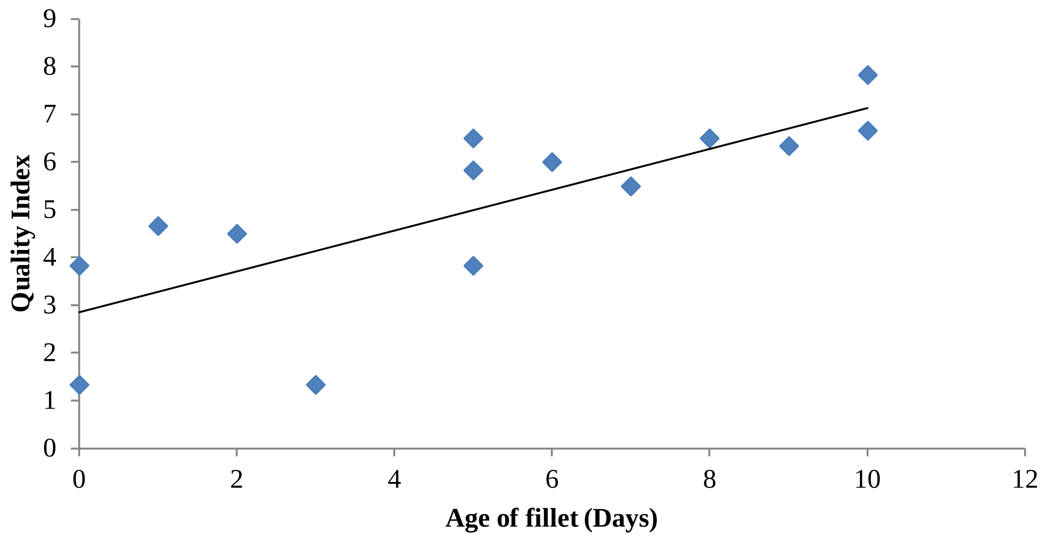

Figure 3.5 Initial quality index relationship with the age of fillets. Line indicates linear regression

Table 3.12 Quality index parameter statistics

Parameter	**Relationship with age of fillet (as an R value)**	**p value**
Texture	0.3919	0.1485
Blood	0.7206	0.0024
Odour	0.8818	0.0000
Colour	0.7071	0.0032
Transparency	0.5156	0.0492
Gaping	-0.0503	0.8587

Therefore, texture and gaping were excluded from the scheme, resulting in Table 3.13.

Table 3.13 Updated Saddletail snapper fillet quality index

Parameter		**Score**
Blood	Pink	0
	Orange	1
	Brown	2
Odour	Fresh seaweed/seawater	0
	Metallic	1

	Sour	2
Colour	Creamy pink/bright sheen	0
	Dull pink	1
	Brown tinge	2
Transparency	Transparent	0
	Opaque	1
	Quality Index	**7**

The relationship between quality index and fillet age with the removal of texture and gaping gave an R value of 0.8283 ($p < 0.0001$), indicating a strong relationship between the new quality index scheme and fillet age (Figure 3.6).

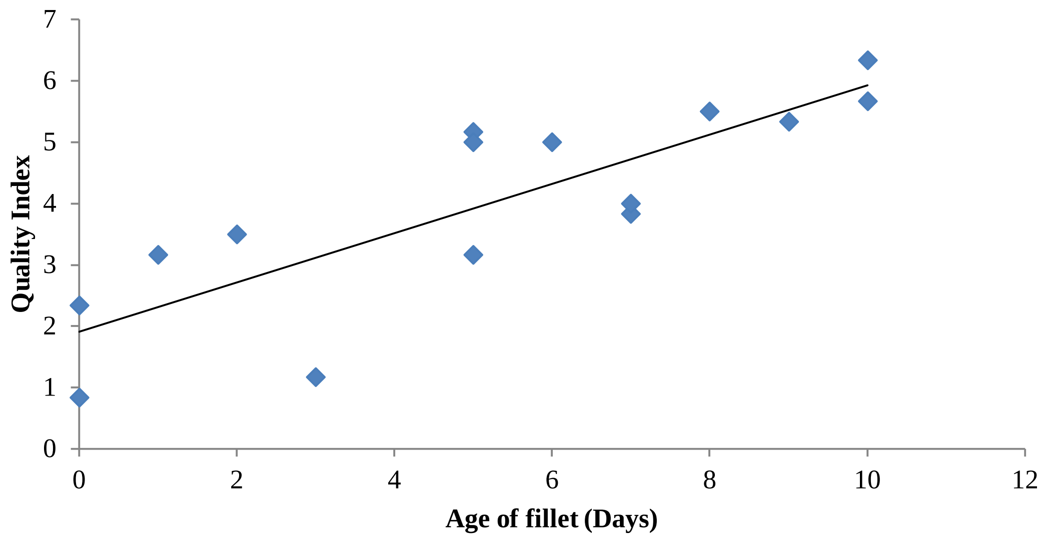

Figure 3.6 Adjusted relationship between quality index and age of fillet. Line indicates linear regression

The Torry scores indicated flavour and odour changed as fillets aged. As Boulter et al. (2009) identified a score of four as the end of shelf life, panellists gave the fillets a seven day shelf life (Figure 3.7).

Microbiology results indicate a strong relationship between total plate count and age of fillets. As the recommended limit of 1,000,000 CFU/g (Sydney Fish Market, 2013) was reached by day five, this indicates five days may be the shelf life of Saddletail snapper fillets (Figure 3.8).

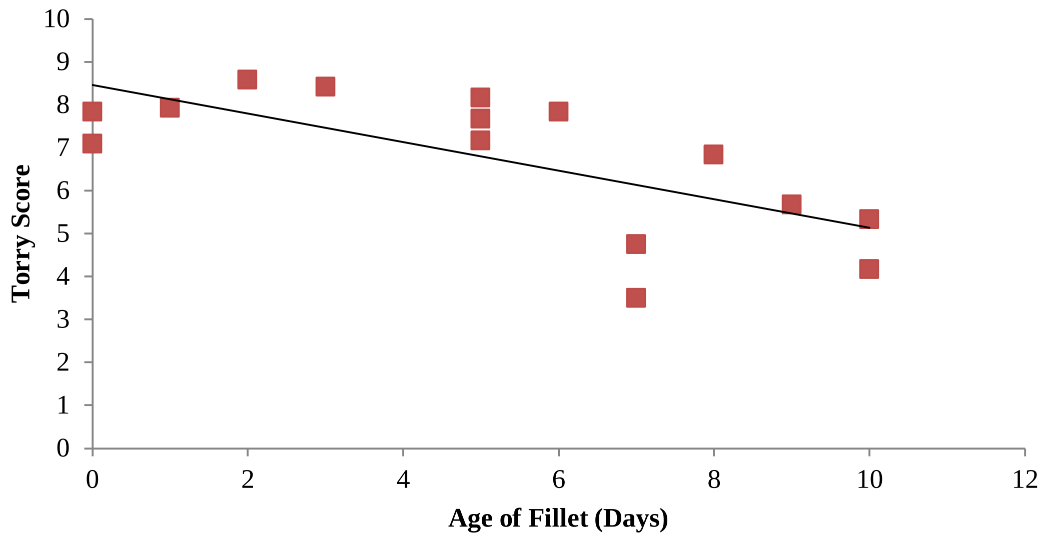

Figure 3.7 Relationship between Torry Score and age of fillet. Line indicates liner regression

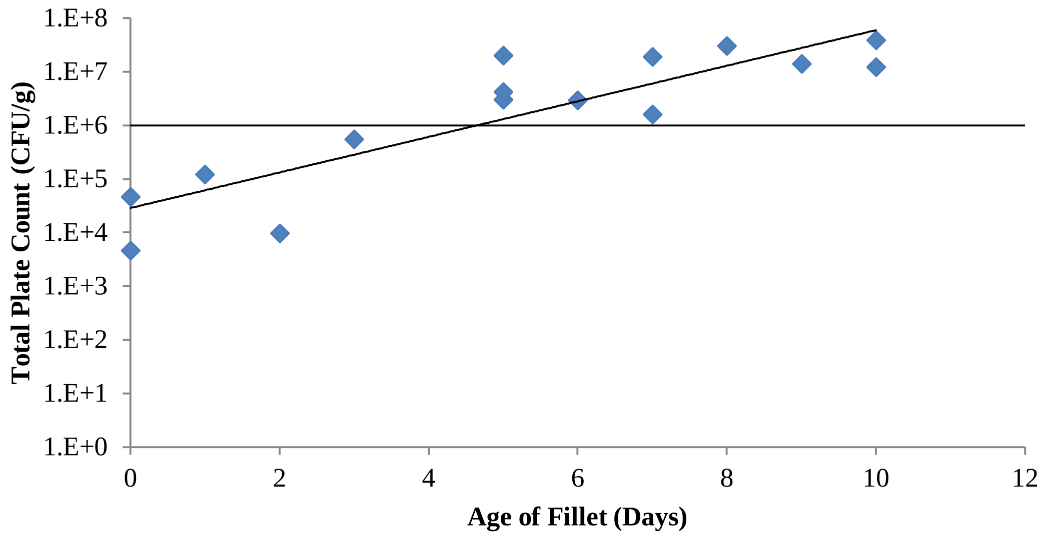

Figure 3.8 Relationship between total plate count and age of fillets. Horizontal line indicates TPC limit found in Sydney Fish Market (2013), diagonal line indicates linear regression

Results were not as clear as hoped as some samples collected had a deep red colour, making the flesh appear older than it was. Fillets also differed in size when a second supplier was sourced partway through the trial. The second supplier sourced much larger and darker fillets, where texture and gaping differed from small fillets.

Table 3.13 was then used in assessing potential cleaner production strategies.

3.6.5. Cleaner production strategy recommendation

Results from each model were compiled and ranked by potential GHG saved, NPV difference, potential GHG saved per NPV, and quality according to the inputs and outputs used in each supply chain and supply chain stage. CPS for each facility and supply chain were selected according to the strategies that suggested a potential reduction in GHG emissions (from the revised PLCA), a potential profit (from the NPV difference), and did not affect the product quality. If more than one potential CPS fitted the described criteria, the one with the highest potential GHG saved per $ 1 of investment was recommended for use in the study.

CHAPTER 4. The Life Cycle Assessment of the Western Australian Finfish Supply Chain

4.1. Introduction

This chapter covers Objective One (Figure 1.1):

1. Identify the areas of greatest greenhouse gas emissions from selected Western Australian seafood supply chains

by measuring three Western Australian finfish supply chains' greenhouse gas (GHG) emissions using a partial life cycle assessment (PLCA). This chapter follows the four steps of PLCA outlined in International Organisation for Standardization (2006): Goal and scope, Life cycle inventory (LCI), Impact assessment and Interpretation (Chapter 3 Section 3.3).

4.2. Goal and scope

The goal was to ascertain and compare the GHG emissions from three Western Australian finfish supply chains. The functional unit was one metric tonne of processed fish sold at retail. The system boundaries of this section included harvesting, processing and retailing of fish fillets, waste disposal and the production and transport of the items purchased, but excluded the cooking and consumption stages of the supply chain and all downstream activities, including food service and restaurant sectors and handling after the product left the retail facility.

4.3. Life cycle inventory

Life cycle inventory (LCI) development is a pre-requisite to assess GHG emissions. Accordingly, a LCI inventory was developed using the quantitative inputs and outputs required to produce one metric tonne of processed fish fillets in the regional, independent and major supply chains. The inputs and outputs are presented in Tables 4.1- 4.5, with results divided into consumable items, energy, transport and outputs.

Tables 4.1 and 4.2 show the inputs and outputs of the regional supply chain respectively. The Harvest stage used relatively few consumable items compared to the processor and retailer. The largest consumable item was water in both the processor and retailer and tubs in the harvest stage. The harvest stage was powered by diesel whereas the processor and retailer were mostly powered by electricity. The processor used more electricity than the retailer and more refrigeration gases than both the harvest and retail stages. Only the processor had filleting waste as the retailer ordered fillets on a daily basis, removing wastage from unsold product. The harvest stage had the most transport inputs. The inputs in Table 4.1 and outputs in Table 4.2 have been incorporated into Simapro LCA software to calculate GHG emissions and identify which supply chain stage produced the most emissions. Then the 34 inputs and outputs were assessed to identify which were the greatest hotspots requiring cost-effective mitigation strategy to further reduce GHG emissions without affecting the quality of fish fillets.

Table 4.1 Inputs per metric tonne of fish fillets from the Regional Supply Chain

	Unit	**Harvest**	**Processer**	**Retailer**
Whole fish	t		2.67	
Fillets	t			1
Consumable Items				
<u>Packaging items</u>				
Checkout paper bags	kg			53.2
Esky	kg		47.4	33.9
Fillet covers	kg			13.9
Pallet wrap	kg	0.11		
Paper to wrap purchase	kg			47.8
Plastic bag for fillet	kg			13.8
Polypropylene bags	kg	2.04		
Tubs	kg	7.72		
<u>Cleaning agents</u>				
Carton liners	kg	3.22	11.2	
Detergent	kg	1.36	3.97	11.7
Hand sanitiser	kg		0.89	6.22
Hand soap	kg			3.11
Paper towels	kg		14.2	
<u>Boat maintenance</u>				
Grease	kg	0.31		

	Unit	Harvest	Processer	Retailer
Hydraulic oil	kg	1.27		
Lanolin grease	kg	0.00072		
Rope	kg	1.1		
Rust rinse	kg	4.03		
Other				
Disposable gloves	kg		0.21	12.8
Ice	kg		215	
Water	kg		25 900	19 300
Energy				
Batteries	kg		0.1	
Diesel	L	2 850		
Electricity	kWh		8 100	5 820
Transport				
Rail	tkm	5.93	13.8	40.7
Refrigerated transport	tkm		96.7	
Ship	tkm	153		
Articulated truck	tkm	101	96.7	544
Light commercial vehicle	km	48.5	107	315

Table 4.2 Outputs per metric tonne of fish fillets from the Regional Supply Chain

	Unit	Harvest	Processer	Retailer
Whole fish	t	2.67		
Fillets	t		1	1
R404a refrigerant	kg	0.49	0.95	3.05
Fish waste	kg		1 670	
GHG emissions			See Table 4.7	

Similarly, Tables 4.3 and 4.4 show the inputs and outputs from the independent supply chain respectively. Again, the harvest stage used relatively few consumable items compared to the retailer. The largest consumable item was water in retailer and tubs in the harvest stage. The harvest stage was powered by diesel whereas retailer was powered by electricity. The independent supply chain differed from the regional supply chain as the independent retailer used more refrigeration gases, electricity and transport (due to refrigerated transport to Perth) than the regional processor and retailer. As the independent retailer was owned by the same company and sold the same species as the regional processor and retailer, the filleting yields were averaged, providing the same quantity of waste per tonne of fillets. The Independent Retailer did sell whole fish, it was excluded from Table 4.4 as it is beyond the scope of this research.

Table 4.3 Inputs per metric tonne of fish fillets from the Independent Supply Chain

	Unit	Harvest	Retailer
Whole fish	t		2.67
Consumable Items			
<u>Packaging items</u>			
Carton liners	kg	3.22	
Checkout plastic bags	kg		15
Fillet covers	kg		8.96
Pallet wrap	kg	0.11	
Paper to wrap purchase	kg		178
Plastic bag for fillet	kg		14.8
Polypropylene bags	kg	2.04	
Tubs	kg	7.72	
<u>Cleaning agents</u>			
Detergent	kg	1.36	9.12
Hand sanitiser	kg		0.83
Hand soap	kg		0.96
Paper towels	kg		20.7
<u>Boat maintenance</u>			
Grease	kg	0.31	
Hydraulic oil	kg	1.27	
Lanolin grease	kg	0.00072	
Rope	kg	1.1	

	Unit	Harvest	Retailer
Rust rinse	kg	4.03	
Other			
Disposable gloves	kg		11.9
Water	kg		2 850
Energy			
Diesel	L	2 850	
Electricity	kWh		91 500
Transport			
Articulated truck	tkm	101	
Light commercial vehicle	km	48.5	353
Rail	tkm	5.93	
Refrigerated transport	tkm		3 380
Ship	tkm	153	

Table 4.4 Outputs per metric tonne of fish fillets from the Independent Supply Chain

	Unit	Harvest	Retailer
Whole fish	t	2.67	
Fillets	t		1
R404a refrigerant	kg	0.49	7.83
Fish waste	kg		1 670
GHG emissions		See Table 4.8	

Tables 4.5 and 4.6 show the inputs and outputs of the major supply chain respectively. The harvest stage used relatively few consumable items compared to the processor and retailer. The largest consumable item was water in both the processor and retailer and tubs in the harvest stage. The harvest stage was powered by diesel whereas the processor and retailer were mostly powered by electricity. The processor used more electricity than the retailer and more refrigeration gases than both the harvest and retail stages. The processor had more filleting waste than the retailer.

Table 4.5 Inputs per metric tonne of fish fillets from the Major Supply Chain

	Unit	Harvest	Processer	Retailer
Whole fish	t		2.26	
Fillets	t			1
Consumable Items				
<u>Packaging items</u>				
Boxes	kg		552	
Carton liners	kg	2.68	12	
Esky	kg		17.9	
Pallet wrap	kg	0.0917	19	
Paper wrapping	kg			2.89
Plastic bag for fillet	kg			0.67
Polypropylene bags	kg	1.7		
Tubs	kg	6.43		
Vacuum bags	kg		75	
<u>Cleaning items</u>				
Bench spray	kg			0.29
Detergent	kg	1.13	48.7	
Degreaser	kg		23	
Hand sanitiser	kg		1	0.12
Hand soap	kg		2.3	0.019
Paper towels	kg			0.77
<u>Boat maintenance</u>				
Grease	kg	0.258		
Hydraulic oil	kg	1.06		
Lanolin grease	kg	0.0006		
Rope	kg	0.917		
Rust rinse	kg	3.36		
<u>Other</u>				
Disposable gloves	kg		7.36	0.19
Hairnets	kg		1.15	
Water	kg		1 440	578

	Unit	Harvest	Processer	Retailer
Energy				
Diesel	L	2 380		
Electricity	kWh		3 870	130

Table 4.6 Outputs per metric tonne of fish fillets from the Major Supply Chain

	Unit	Harvest	Processer	Retailer
Whole fish	t	2.26		
Fillets	t		1	1
R404a refrigerant	kg	0.409	0.8	3.19
Fish waste	kg		1 260	50
GHG emissions			See Table 4.9	

4.3.1. LCI supply chain comparisons

The comparisons above were similar in all three supply chains. The independent supply chain did acquire the burden of a processor as they process the fillets on site. They also had a large refrigerated transport tkm result as the fish travelled to Perth.

The harvest stage required less inputs to produce one metric tonne of fillets within the major supply chain as the city processor had a higher filleting yield than the regional processor and independent retailer. Although the harvest stage caught the same amount of fish, retaining a larger portion after filleting results in less inputs required.

4.4. Impact assessment

The impact assessment involved connecting each item in the LCI to the relevant emission factor. The LCI was multiplied by the respective emission factors to determine the total GHG emissions from each supply chain and a sensitivity analysis performed.

The LCI was then multiplied by the respective emission factors.

4.4.1. Greenhouse gas emissions from the supply chains

Once the input values of the LCI of the regional, independent and major supply chains (Section 4.3) were inserted into the Simapro LCA software, they were multiplied by the respective emission factors. The resulting GHG emissions are presented by supply chain in Tables 4.7-4.9. Again, the results were divided into consumable items, energy, transport and output categories.

Table 4.7 shows the GHG emissions from the regional supply chain. Harvest had the least GHG emissions, followed by the retailer and the processor. Energy had the greatest GHG emissions in all sectors.

Table 4.7 GHG emissions from the Regional Supply Chain (kg CO_2 –eq per metric tonne of fish filets)

	Harvest	**Processer**	**Retailer**	**Total**
Consumable Items				
Packaging items				
Carton liners	6.28	21.8		**28.1**
Esky		306	218	**524**
Fillet covers			7.75	**7.75**
Pallet wrap	0.288			**0.288**
Paper checkout bags			28.3	**28.3**
Paper wrapping			25.5	**25.5**
Plastic bag for fillet			35.0	**35.0**
Polypropylene bags	8.32			**8.32**
Tubs	4.31			**4.31**
Cleaning agents				
Detergent	1.36	2.07	6.09	**9.52**
Hand sanitiser		0.341	2.38	**2.72**
Hand soap			3.17	**3.17**
Paper towels		18.4		**18.4**
Boat maintenance				
Grease	0.125			**0.125**
Hydraulic oil	0.539			**0.539**
Lanolin grease	0.000283			**0.000283**
Rope	4.48			**4.48**

	Harvest	Processer	Retailer	Total
Rust rinse	4.69			**4.69**
Other				
Disposable gloves		0.115	7.12	**7.23**
Water		15.5	11.6	**27.1**
Ice		17.8		**17.8**
Total	**30.4**	**382**	**345**	**757**
Energy				
Batteries		2.27		**2.27**
Diesel	1 990			**1 990**
Electricity		7 440	5 350	**12 800**
Total	**1 990**	**7 440**	**5 350**	**14 800**
Transport				
Rail	0.0623	0.145		**0.208**
Refrigerated transport		7.80		**7.80**
Ship	0.55			**0.55**
Articulated truck	8.23	14	56	**78.2**
Light commercial vehicle	17.3	60	176	**254**
Outputs				
R404a refrigerant	479	386	1 240	**2 110**
Fish waste		2 310		**2 310**
Total	**479**	**2 700**	**1 240**	**4 420**
Total	**2 530**	**10 600**	**7 160**	**20 300**

Table 4.8 shows the GHG emissions from the independent supply chain. The retailer had 35 times the GHG emissions than the harvest stage. Energy had the greatest GHG emissions in both sectors.

Table 4.8 GHG emissions from the Independent Supply Chain (kg CO_2 –eq per metric tonne of fish filets)

	Harvest	**Retailer**	**Total**
Consumable Items			
<u>Packaging items</u>			
Carton liners	6.28		**6.28**
Fillet covers		5	**5**
Pallet wrap	0.288		**0.288**
Plastic checkout bags		29.2	**29.2**
Paper wrapping		94.7	**94.7**
Plastic bag for fillet		37.5	**37.5**
Polypropylene bags	8.32		**8.32**
Tubs	4.31		**4.31**
<u>Cleaning agents</u>			
Detergent	1.36	1.23	**2.59**
Hand sanitiser		0.487	**0.487**
Hand Soap		0.976	**0.976**
Paper towels		26.8	**26.8**
<u>Boat maintenance</u>			
Grease	0.125		**0.125**
Hydraulic oil	0.539		**0.539**
Lanolin grease	0.000283		**0.000283**
Rope	4.48		**4.48**
Rust rinse	4.69		**4.69**
<u>Other</u>			
Disposable gloves		6.61	**6.61**
Water		1.71	**1.71**
Total	**30.4**	**204**	**235**
Energy			
Diesel	1 990		**1 990**
Electricity		84 100	**84 100**
Total	**1 990**	**84 100**	**86 100**

	Harvest	Retailer	Total
Transport			
Rail	0.0623		**0.0623**
Refrigerated transport		9.91	**9.91**
Ship	0.55		**0.55**
Articulated truck	8.23		**8.23**
Light commercial vehicle	17.3		**17.3**
Total	**26.2**	**9.91**	**36.1**
Outputs			
R404a refrigerant	479	3 190	**3 670**
Fish waste		2 310	**2 310**
Total	**479**	**5 500**	**5 980**
Total	**2 530**	**89 800**	**92 300**

Table 4.9 shows the GHG emissions from the major supply chain. The processor had the most GHG emissions, followed by harvest and retail. Energy had the greatest GHG emissions in all sectors.

Table 4.9 GHG emissions from the Major Supply Chain (kg CO_2 –eq per metric tonne of fish filets)

	Harvest	Processer	Retailer	Total
Consumable Items				
Packaging items				
Boxes		231		**231**
Carton liners	5.23	11.6		**16.9**
Eskies		57.8		**57.8**
Pallet wrap	0.24	24		**24.3**
Paper wrapping			1.54	**1.54**
Plastic bag for fillet			1.71	**1.71**
Polypropylene bags	6.93			**6.93**
Vacuum bags		190		**190**
Tubs	3.59			**3.59**

	Harvest	Processer	Retailer	Total
<u>Cleaning agents</u>				
Bench spray			0.546	**0.546**
Bleach		30.5		**30.5**
Detergent	1.14		0.251	**1.39**
Degreaser		8.62	1.08	**9.7**
Hand sanitiser		0.191	0.046	**0.237**
Hand soap		1.17	0.0189	**1.19**
Paper towels			0.996	**0.996**
<u>Boat maintenance</u>				
Grease	0.104			**0.104**
Hydraulic oil	0.449			**0.449**
Lanolin grease	0.000235			**0.000235**
Rope	3.73			**3.73**
Rust rinse	3.91			**3.91**
<u>Other</u>				
Hairnets		0.249		**0.249**
Disposable gloves		2.05	0.107	**2.16**
Water		0.862	0.347	**1.21**
Total	**25.3**	**558**	**6.64**	590
Energy				
Diesel	1 660			**1 660**
Electricity		1 780	119	**1 900**
Total	**1 660**	**1 780**	**119**	**3 550**
Outputs				
Fish waste		1 750	69.3	**1 820**
R404a refrigerant	400	324	1 300	**2 030**
Total	**400**	**2 080**	**1 370**	**3 850**
Total	**2 080**	**4 410**	**1 500**	**7 990**

4.4.2. Summary

Figure 4.1 shows the total GHG emissions from each supply chain. The independent supply chain had the highest emissions, followed by the regional supply chain and the major supply chain. Within each supply chain, the stage with the highest GHG emissions was where the filleting occurred. In the regional and major supply chains, filleting occurred in the processing stage whereas the independent supply chain filleted at the retailer.

Although the harvest stage processes did not change for separate supply chains, filleting yields within the regional processor, independent retailer and city processor differed, resulting in a different quantity of inputs and outputs per metric tonne of fish in the harvest stage. These filleting yields may differ due to the manager's waste estimate, the skill of the filleter and difference in species quantity (as each species will have a different filleting yield).

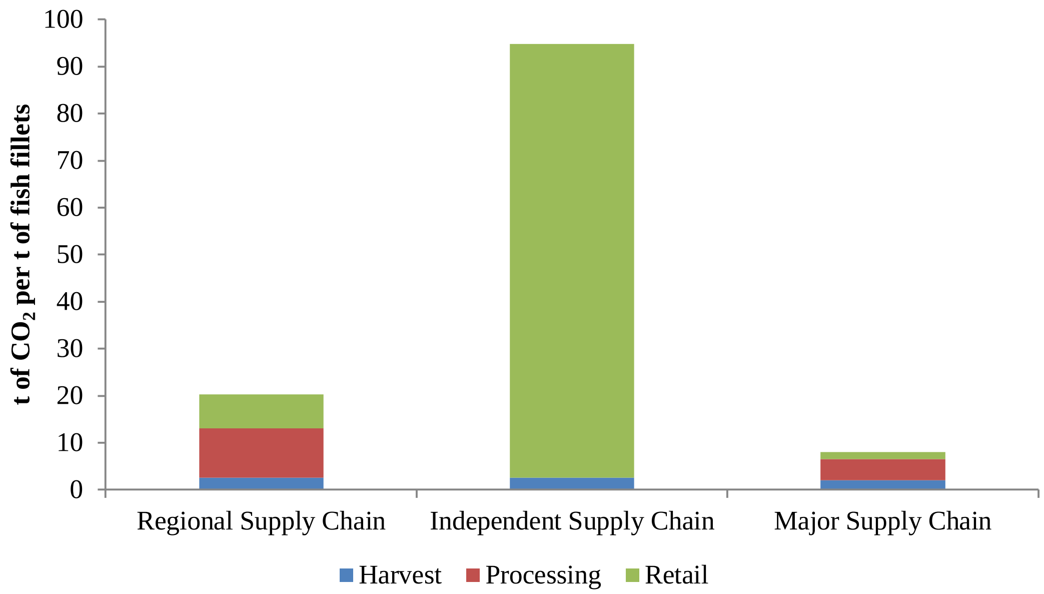

Figure 4.1 Supply chain comparison by sector

4.5. Interpretation

Results were compared to determine areas of greatest GHG emissions firstly between each supply chain, and then between each supply chain sector.

4.5.1. Supply chain comparison

The supply chains in this study were the regional supply chain, independent supply chain and major supply chain.

Producing one metric tonne of fish fillets released a total of 20,300 kg CO_2 –eq from the regional supply chain and 92,300 kg CO_2 –eq from the independent supply chain. The major supply chain had the lowest GHG with 7,990 kg CO_2 –eq (Figure 4.1).

Energy had the greatest GHG emissions from all three supply chains (Figure 4.2). The energy emissions came from batteries (0.02 %, 0 % and 0 %), diesel (13.5 %, 2.3 % and 46.6 %) and electricity (86.5 %, 97.7 % and 53.4 %) in the regional, independent and major supply chains respectively. This highlights the high electricity consumption in the independent and regional supply chains compared to the major supply chain.

The major supply chain also had a relatively high refrigerant emission (28 %) (Figure 4.2). However, the total refrigerant emissions were less than the regional and independent supply chains. As the major supply chain stages were more efficient with their energy use, the areas of greatest GHG emissions differ, even though they may be smaller than the regional and independent supply chains.

Fish waste released 11.4 %, 2.50 % and 22.8 % of GHG emissions in the regional, independent and major supply chains respectively. The regional and independent supply chains had more GHG emissions from waste in total, but due to their large energy consumption, waste had a larger percentage emission from the major supply chain.

The consumable items had a relatively low GHG emission in the regional, independent and major supply chains (3.6 %, 0.25 % and 7.4 % respectively). Within the consumable items in the regional and major supply chains, most of the GHG emissions came from packaging the fillets to travel to the next supply chain stage i.e. in cardboard boxes (0 % and 39 % of consumable items respectively) and polystyrene eskies (71 % and 10% of consumable items respectively). As the independent supply chain did not pack fillets for transport, instead filleting just before point of sale, it had a relatively lower GHG from consumable items, mostly from the paper used to wrap purchases (40 % of consumable items).

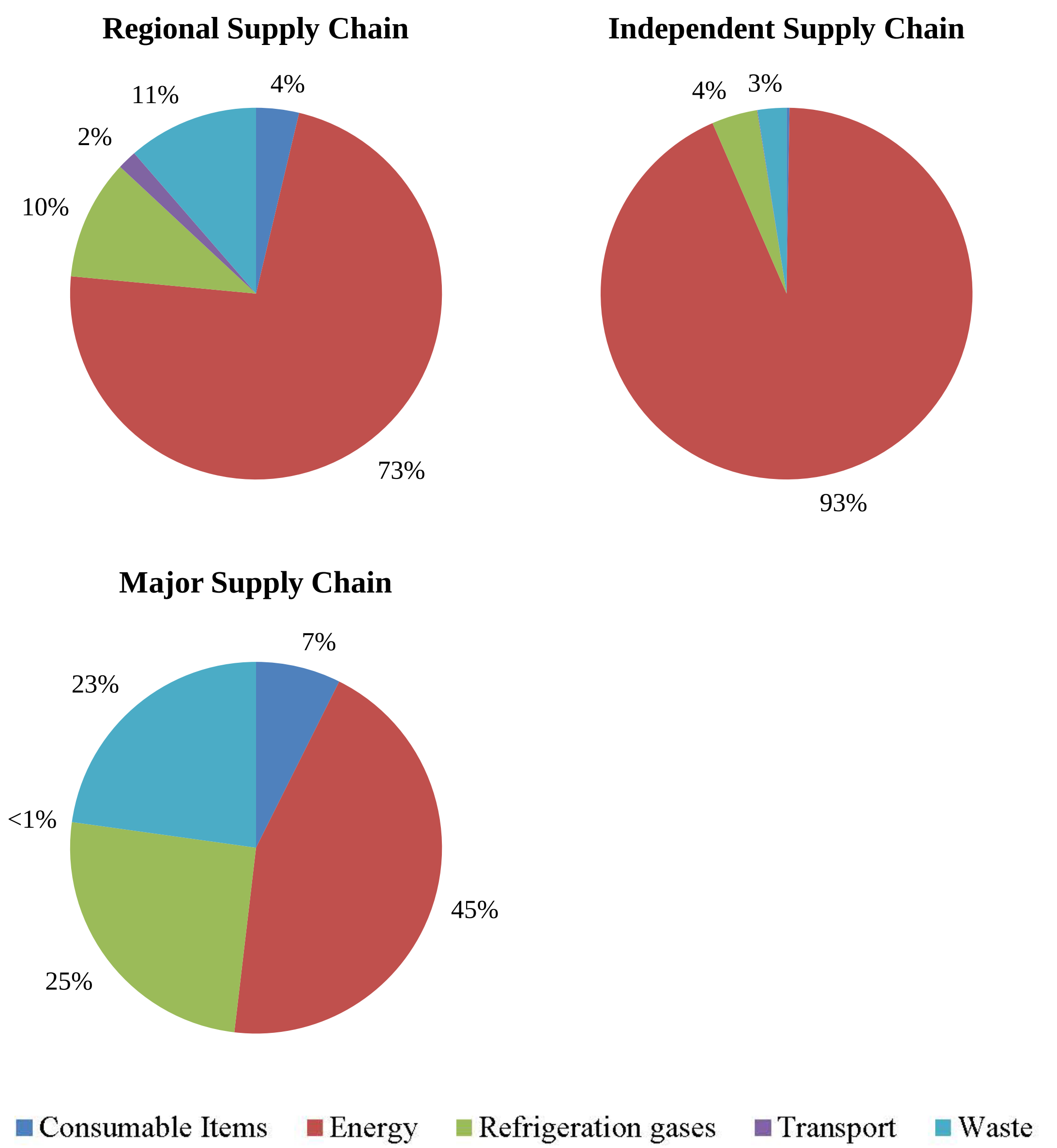

Figure 4.2 Areas of GHG impact in each supply chain

4.5.2. Sector comparison

The sectors in this study were harvest, regional processor, regional retailer, independent retailer (which also processed the fillets), city processor and supermarket. The relative impacts from each sector are shown in Figure 4.3.

The greatest GHG emissions within the harvest, regional processor, regional retailer, independent retailer and city processor sectors, was from energy consumption. These energy emissions from the harvest stage were diesel whilst the regional retailer, independent retailer and city processor only consumed grid electricity. The only combination of energy was electricity (99.97 %) and batteries (0.03 %) from the regional processor. Of the energy consumption, the independent retailer consumed

11 and 47 times the electricity per metric tonne of fish than the regional and city processors respectively.

The individual sectors that consumed the most energy were the regional and independent retailers, harvest and regional processor (74.6 %, 93.6 %, 78.8 % and 70.2 % of the sector GHG emissions respectively).

Refrigeration gases had the greatest impact in the supermarket stage and the second greatest impact in the harvest, regional retailer and independent retailer stages. This high result was influenced by the Australian Government legislation reducing the R22 refrigerant from 2012 with the intention of removing it completely by 2016 (Department of the Environment, 2014b). This, along with the subsequent increase in R22 price, resulted in the replacement of refrigeration equipment with R404a refrigerant due to the relatively cheap equipment in Australia.

The sectors that consumed the most refrigerant were the retailers (17.3 %, 3.6 % and 86.9 % of the GHG emissions in the regional and independent retailers and supermarket sectors respectively). One possible reason for this trend is that the harvest and processors were storing the fish whole (and transporting fillets soon after filleting). Whole fish have a smaller ratio of surface area to weight than fillets, meaning fillets are more susceptible to temperature fluctuations. Fillets are also spread out in display cabinets for customer viewing on a daily basis where a large headspace within the cabinet remains empty. Whilst this may be a sales technique as customers have a good view of each product, it does mean empty space is being cooled in the cabinet, using more refrigerant (and possibly electricity) per metric tonne of product than a cool room.

Fish waste also had an impact in the regional processor and the city processor. One reason for this is the large quantity of product wasted. The regional processor and independent retailer had an average filleting yield of 37.5 % and the city processor 45 %. These yields differ according to the skill of the filleter and the species. All three filleting stages disposed of more than half the product, leaving it to anaerobic digestion in landfill. Despite this large wastage, filleting waste was only 2.6 % of the

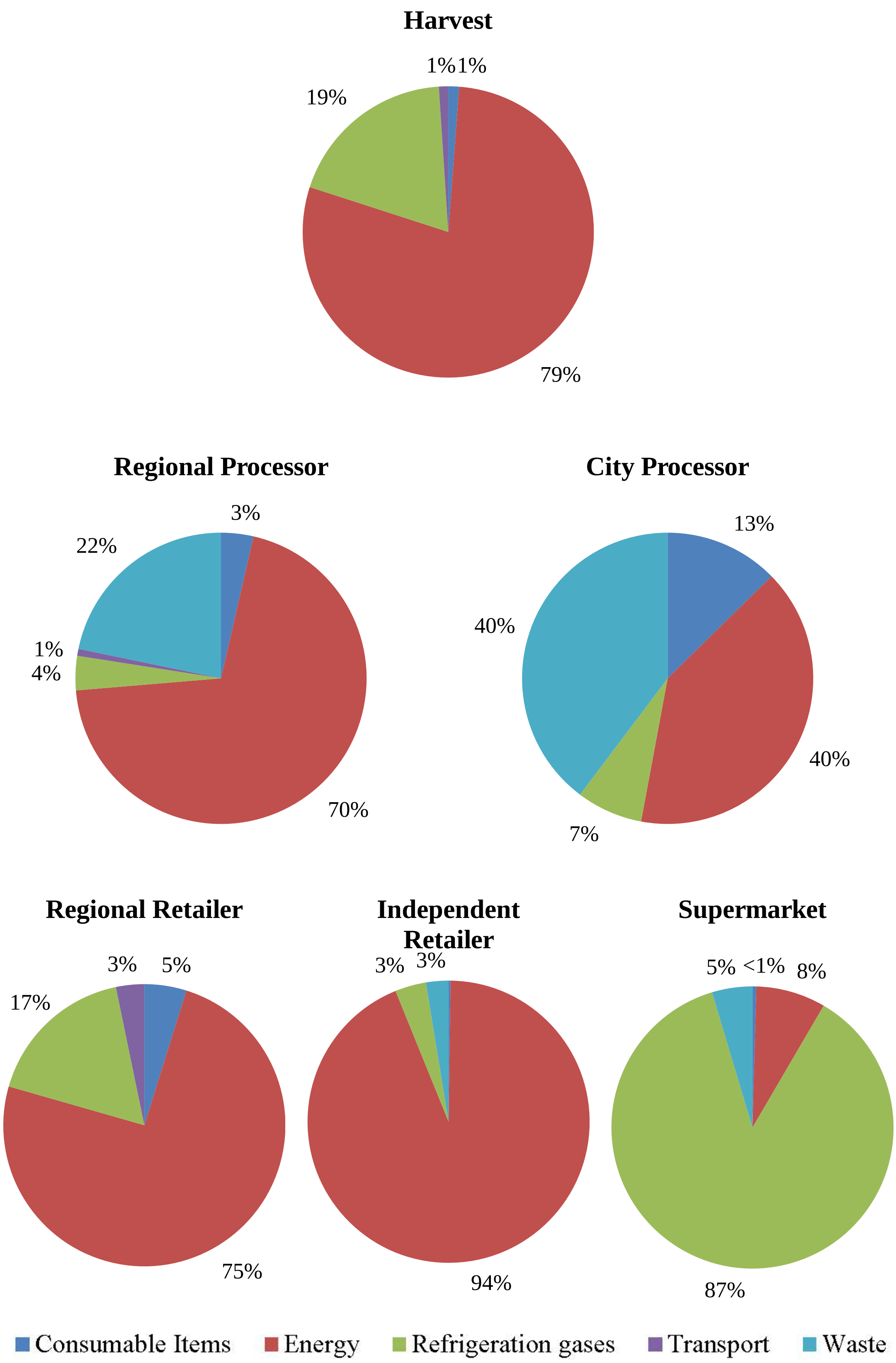

Figure 4.3 Areas of GHG impact in each supply chain stage

GHG emissions in the independent retailer, due to the large GHG emission from electricity consumption.

The city processor also had a 12.6% GHG emission from consumable items. The consumable item with a large GHG emission was the cardboard boxes (41 % of consumable items) used to pack the fish in. The regional supply chain used polystyrene eskies for the same purpose, resulting in a higher GHG emission per metric tonne of fish fillets (305.5 and 57.8 kg CO_2 –eq in the regional and city processors respectively), but due to the higher energy consumption in the regional processor, had a lower percentage emission within the stage.

4.5.3. Limitations

As the supermarket was unclear in the quantities of detergent, hand soap, drain cleaner, bench spray and hand sanitiser consumed (stating 1 per week without stipulating whether 1 L or carton), the largest package available from the suppliers was assumed for the hand soap (800 mL), detergent (20 L), drain cleaner (20 L) and bench spray (6 L) and hand sanitiser (20 L). Hence, these chemical quantities were overestimated rather than underestimated.

The supermarket were also unable to provide refrigeration gas quantities for confidentiality reasons. Therefore, the average refrigeration gas quantity per metric tonne of fish between the independent retailer, city processor, regional processor and regional retailer was used as an estimate.

The city processor and supermarket did not provide supplier locations for transport data. Consequently, transport was excluded when comparisons between the supply chain and stages occurred.

4.6. Sensitivity analysis

4.6.1. Supply chain

The Monte Carlo Simulation of each supply chain found the standard deviations were only 2.6 %, 3.8 % and 1.3 % of the mean values of the GHG emissions from the regional, independent and major supply chains respectively, confirming the validity of this PLCA (Table 4.10).

Table 4.10 Monte Carlo simulation uncertainty analysis of each supply chain (1,000 runs) in kg CO_2 –eq per metric tonne of fish fillets

	Actual Value	**Mean**	**Standard Deviation**	**Standard Error of Mean**
Regional supply chain	20 300	21 800	566	0.000823
Independent supply chain	92 300	91 600	3 500	0.00121
Major supply chain	7 990	7 190	92.8	0.000408

4.6.2. Sectors

The Monte Carlo Simulation of each sector found the standard deviations were only 2.3 %, 3.0 %, 2.8 %, 3.8 %, 2.0 % and 0.36 % of the mean values of GHG emissions from the harvest, regional processor, regional retailer, independent retailer, city processor and supermarket respectively (Table 4.11). As the only difference in the harvest stage between supply chains was the yield (i.e. all inventory items were of the same proportion), only the quantities from the regional and independent supply chains were used in this analysis.

Table 4.11 Monte Carlo simulation uncertainty analysis of each supply chain stage (1,000 runs) in kg CO_2 –eq per metric tonne of fish fillets

	Actual Value	**Mean**	**Standard Deviation**	**Standard Error of Mean**
Harvest	2 530	2 510	56.9	0.000716
Regional Processor	10 600	11 000	331	0.000948
Regional Retailer	7 160	8 150	230	0.000891
Independent Retailer	89 800	88 900	3 400	0.00121
City Processor	4 410	3 600	71.9	0.000632
Supermarket	1 500	1 500	5.4	0.000114

4.7. Discussion

4.7.1. Comparison of supply chain studies

When comparing these results to previously published work, few studies had the same areas of greatest impact perhaps because they did not include the whole supply chain (Ellingsen et al., 2009; Svanes et al., 2011b; Vázquez-Rowe et al., 2013; Winther et al., 2009; Ziegler et al., 2013). Previous seafood PLCA studies either focussed on the harvest supply chain stage, where energy use was diesel (Ellingsen and Aanondsen, 2006; Svanes et al., 2011a; Winther et al., 2009) or focussed on the processing and retail stages that require electricity used in processing (Vázquez-Rowe et al., 2013; Winther et al., 2009).

4.7.2. Comparison between sectors

The harvest stage (described in Section 3.3.1) within this study had energy, specifically diesel as a GHG hotspot. This is consistent with previous research from Thrane (2006), Vázquez-Rowe et al. (2011a), Vázquez-Rowe et al. (2010b), and Vázquez-Rowe et al. (2011b) identifying diesel as the greatest GHG emission. When comparing Australia's fuel use to international studies, Parker et al. (2015) found fuel use was higher in Australia. One reason for this is Australia's high seafood prices mean the industry are not under as much financial pressure to reduce their consumption. The Australian industry also benefitted from the fishery exclusion from the carbon tax before its repeal in 2014, receiving the tax breaks, thus providing less financial incentive to reduce consumption (Parker et al., 2015). However, fuel use does differ between the species caught, as Parker and Tyedmers (2014) highlighted that most of Australia's fishery fuel use is from crustaceans, rather than finfish.

The processing sector in this study had energy and waste with the greatest GHG emissions. Again, there is little research in the fish processing sector. Whilst Thrane et al. (2009a) developed potential cleaner production strategies, no initial LCA was applied to find the areas of greatest environmental impact. Fet et al. (2010) found the box used to transport fish and the transportation stage to have the most GHG emissions. Similarly, Hospido et al. (2006) found packaging to have the highest GHG emissions, but with cans rather than boxes or polystyrene. Although fish waste recycling was investigated (Archer et al., 2005; Howieson et al., 2013; Kafle et al., 2013; Parker and Tyedmers, 2012b; Rubio-Rodríguez et al., 2012) no GHG emissions from seafood waste in landfill have been previously calculated, making this study unique in the inclusion of fish waste disposal GHG emissions.

The retail sectors in this study (described in Section 3.3.3) had energy and refrigerants as areas of greatest GHG emissions. There is little research on the retail stage and its effects on GHG hotspots. General retail research indicates the refrigeration units selected (Cecchinato et al., 2010; Cortella, 2002), energy consumption (Tassou et al., 2011) and waste disposal (Heller and Keoleian, 2014; Scholz et al., 2015) are areas of greatest GHG impact, consistent with this study. However, as these are general studies, none assessed refrigeration, energy and waste disposal together, rather, choosing refrigeration, energy or waste to focus on. Therefore, this research is unique in that it measures the GHG emissions of finfish in a retail setting, taking into account all aspects including refrigeration, energy and waste.

4.7.3. Areas of greatest impact

This study categorised GHG emissions into consumable items, energy, storage, transport and waste. Energy, storage and waste were found to have the greatest GHG impacts in the supply chains measured, specifically from electricity, refrigeration gases and landfill respectively. Polystyrene eskies had the greatest emissions from the consumable items in the regional supply chain.

Energy consumption was also the hotspot in other seafood PLCA studies. However, in this study, electricity in processing and retail had the greatest GHG emissions, rather than diesel consumption in the harvest stage as found by Winther et al. (2009), Thrane (2004), and Vázquez-Rowe et al. (2010b, 2011b) or in bait production (Mungkung et al., 2013; Vázquez-Rowe et al., 2011b).

In comparison to other meat industries, fresh fish had a small electricity consumption per metric tonne of product in Netherlands (Wang, 2008) (i.e. fresh fish consumed 39.5 kwh per metric tonne compared to 104.4 and 308.6 kwh per metric tonne from beef and chicken respectively). This difference accounts for the feed production required to raise the beef and chicken, whereas this fish study included wild caught fish. Frozen fish though, had a large electricity consumption (186.2 kwh per t) (Wang, 2008) demonstrating that freezing and storing fish results in both increased GHG emissions and increased electricity costs. The energy consumption from fresh and frozen fish production was lower in Netherlands (Wang, 2008) than in this study as Netherlands has a different climate to Western Australia, resulting in more energy to cool and maintain temperature (8,099, 91,510 and 3,869 kwh per metric tonne of fillets in the regional processor, independent retailer and city processor respectively). Whilst refrigeration energy is a hotspot in finfish processing, it is not in meat processing (enteric emissions) (Peters et al., 2010) or chicken processing (feed production) (Bengtsson and Seddon, 2013). As a result, wild caught finfish fillets have a lower GHG emission than its competitor meat products.

Refrigeration gases had 11 %, 4 % and 28 % from the regional, independent and major supply chains respectively. However, previous seafood studies have ignored the refrigeration gas in LCA studies altogether, underestimating the GHG emissions. Vázquez-Rowe et al. (2013), Ziegler (2013) and Svanes (2011b) found refrigerant leakage to be a hotspot during harvest but did not measure beyond harvest into processing and further handling. Although Iribarren (2010c) originally did not include refrigerants in his research, in a later study he found refrigerant leakage to have the greatest carbon emissions from fish capture (Iribarren et al., 2011). Other studies including Thrane (2006) and Vázquez-Rowe (2011b) ignored refrigeration completely in their research. Winther (2009) did include refrigerants, but the study comprised of carbon neutral alternatives. As a result, the energy used in the harvest was the hotspot (Thrane, 2006; Vázquez-Rowe et al., 2011b; Winther et al., 2009; Ziegler et al., 2013) with minimal GHG from processing and retail.

Filleting waste contributed to a large portion of solid waste (up to 62.5 %) and 7 %, 2 %, 15 % of GHG emissions in the regional, independent and major supply chains respectively. Previous studies have indicated waste after filleting to be 58 % of gutted fish (Archer et al., 2001) and 67 % of whole fish (Ng, 2010; Thrane, 2006), although yields vary with species (Archer et al., 2001). This waste is not only unused product, but when dumped in landfill, breaks down via anaerobic degeneration to produce 0.3516 kg of CH_4 per kg of waste (Chen et al., 2010), with only 39.8 % potentially recovered for bioelectricity production (Department of the Environment). Thus landfill does account for 5.29 kg CO_2 –eq per kg of fish fillet. However, despite the high yield of solid waste, other finfish PLCA studies excluded filleting waste from their PLCA studies (Ellingsen et al., 2009; Winther et al., 2009), or were unclear in the waste disposal method and emission factor (Thrane, 2006). One reason for this may be the attitude towards waste recycling in countries where seafood has a larger market. For example, when realising tails were lost after freezing the product, the processor immediately changed the process to isolate the tails as a by-product before freezing, seeing the situation as lost profit (Thrane et al., 2009a). Brazilian fish processors successfully reduced their solid waste by 31%, by recycling into fishmeal, resulting in a profit of $ 17-18.50 USD per metric tonne of fish processed

(Bezama et al., 2012). Other processors immediately sold waste to pet food producers (Ziegler et al., 2003) or made into milk fodder (Thrane, 2006).Therefore, research is required to convince Western Australian finfish processors that filleting waste is not a burden to be disposed of as cheaply as possible, but rather an asset of which can be sold or further processed.

Whilst the supply chains measured required long distant transport (> 1,000km), the transportation had a minimal impact in the regional (2 %) and city (0.04 %) supply chains. This is because each consumable item purchased had a relatively low weight, resulting in a low tkm. Transport of fish to the city retail outlet had a larger impact than transporting the consumable items to the vessel, regional processor and regional retailer, but was still insignificant in comparison to energy, storage and waste. Other seafood SCLA studies had similar results with mussels (Iribarren et al., 2010a) and finfish (Ellingsen et al., 2009; Thrane, 2006; Vázquez-Rowe et al., 2011b; Ziegler et al., 2011). However, this does not include transport by air, which significantly increases the GHG emissions as demonstrated in Winther et al. (2009)

Packaging fish fillets for transport was not the highest GHG emission, but of the two processing facilities, the regional processer that used polystyrene eskies had a larger GHG emission than the city processor that used cardboard boxes. Despite more cardboard boxes used in the city processor per metric tonne of fish, polystyrene eskies had a larger emission factor. Tan and Khoo (2005) compared life cycle and end of life scenarios of polystyrene and corrugated cardboard used for electronic packaging, showing polystyrene had both a higher GHG in production and end of life in landfill than corrugated cardboard. GHG emissions are only one problem with polystyrene eskies as they are a single use item, and there are few (none in regional areas) facilities that recycle, causing large quantities of landfill in Western Australia. Whilst cardboard boxes may also be disposed of in landfill, recycling options are more readily available. Cardboard also has the option of lying flat when not in use, using less space and thus, reducing landfill costs. Consequently, research into the feasibility of packaging fish fillets in cardboard boxes within the regional supply chain requires further investigation.

4.8. Conclusion

The Western Australian finfish supply chain's GHG emissions have been determined and an overall strategy designed with the aim of providing benefits for the environment and industry. Important research findings determined the sectors that filleted the fish, had the highest emissions overall (the regional processor, independent retailer and city processor). Other findings determined that harvest sector had the lowest impact on emissions, followed by retail and processing. The major supply chain had the lowest GHG emissions, followed by the regional supply chain and the independent supply chain.

The greatest GHG emissions in each supply chain were from energy mainly from electricity consumption. GHG emissions from refrigeration gases and waste emissions followed.

Energy also caused the most GHG emissions in the harvest, regional and city processors, and the regional and independent retailers, followed by filleting waste disposal (in the regional and city processors) and refrigerants (harvest, regional retailer and independent retailer). Refrigerants were the main GHG emissions in the supermarket chain. The energy usage came from diesel in the harvest stage and electricity in all other stages. There was a greater use of polystyrene eskies by the regional processor. In contrast there was a greater use of cardboard boxes by the city processor which a lower GHG emission.

Thus a combination of the whole Western Australian seafood supply chain GHG emissions provided a more effective picture of environmental supply chain management. The research determined a combination of these strategies have the potential to reduce up to 35% of the total GHG emissions from fillet harvest, processing and retail. A major outcome of this research will be the enhancement of the framework of different seafood supply chains and enabling finfish companies throughout Western Australian to restructure their supply chain to reduce GHG emissions by implementing Cleaner Production Strategies.

Chapter 5 will explore potential cleaner production strategies to mitigate the areas of greatest impact from the three supply chains measured: electricity consumption, refrigerant emission and packaging fillets in polystyrene eskies.

CHAPTER 5. Implication of Cleaner Production Strategies in the Western Australian Finfish Supply Chains

5.1. Introduction

This chapter includes the development and modelling of potential cleaner production strategies (CPSs) to mitigate the areas of greatest greenhouse gas (GHG) emissions identified in Chapter 4. The aim of this chapter is to achieve Objectives 2 and 3 (Figure 1.1):

2. Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs
3. Recommend intervention strategies to reduce the GHG emissions from the Western Australian finfish supply chain

Results described in Chapter 4 indicated electricity, refrigeration gases and fish waste had the most GHG emissions in all supply chains measured, and polystyrene packaging in the regional supply chain.

CPSs already used in the seafood industry were reviewed in Paper 1, Section 2.7. This review indicated the refrigeration could be mitigated by good housekeeping by superchilling the fish (Blowers and Lownsbury, 2010; Svanes et al., 2011b; Winther et al., 2009), technology modification of changing the refrigerator (Blowers and Lownsbury, 2010; Vázquez-Rowe et al., 2013; Winther et al., 2009) and product modification of removing the head and tail to increase edible space in the refrigerator (Claussen et al., 2011; Thrane et al., 2009a). As the product was already filleted, removing the head and tail was not an option. Superchilling would also change the product within a retail setting, influencing the customers' choice. Therefore, the technological modification of variable speed drives to reduce energy consumption and solar and biogas energy to replace electricity consumption (input substitution) were investigated.

This review also indicted waste products such as hydrolysate and dried products had further economic opportunities. The opportunity to investigate a waste product for human consumption (fish mince) also indicated a potential economic opportunity.

The packaging CPSs were chosen as seafood can be packed in expanded polystyrene boxes (eskies), solid fibreboard boxes, corrugated fibreboard boxes, corrugated plastic boxes, returnable plastic boxes and bulk modified atmosphere packs (SeaFish, 2009). On consultation with packaging suppliers to Western Australia, cardboard boxes designed for fish transport with and without an air gap (a second layer of cardboard within the box designed to trap air to create further insulation) were assessed against the current polystyrene esky. Solid fibreboard boxes and corrugated boxes were not recommended by these suppliers and bulk modified atmosphere packs involve unnecessary processing that will increase packaging time. Reusable eskies were not assessed as the partnering industry were not interested.

Therefore, the CPSs investigated for each hotspot are listed in Table 5.1

Table 5.1 CPSs investigated in this chapter and their category according to UNEP (2002)

Hotspot	CPSs investigated	Type of CPS
Electricity (Section 5.2)	Variable speed drives	Technological modification
	Solar electricity	Input substitution
	Biogas electricity	Technological modification and waste recycling
Refrigeration gases (Section 5.3)	Replacing equipment with R134a	Technological modification and input substitution
Recycling filleting waste (Section 5.4)	Hydrolysate	Waste recycling
	Drying	Waste recycling
	Mincing	Waste recycling
Fillet packaging (Section 5.5)	Cardboard boxes	Input substitution

A partial life cycle assessment (PLCA), economic analysis and quality assessment was undertaken for each CPS investigated (as appropriate).

5.2. Electricity

The impact of electricity CPSs were assessed using PLCA, economic assessments and quality assessments. These strategies included variable speed drive installation on all refrigeration and freezer units (a good housekeeping CPS), and electricity substitution using solar and biogas (input substitution CPSs).

A variable speed drive is a device that regulates the speed of the refrigerator motor (Saidur et al., 2012), resulting in noise reduction, motor start-up softening and electricity reduction (McIntosh, 2014).

Solar electricity is useful for supplementing the bulk of the power used during the day. As the electricity consumption from the partnering firms was predominantly from refrigeration and freezing, it is assumed electricity consumption is consistent over a 24 hour period. Therefore, solar panels can either be used to supplement grid electricity during the peak sun hours of the day, or by using batteries to store electricity for the time outside of the peak sun hours. Peak sun hours are the time per day the sun provides the maximum solar electricity, these differ for the various locations around Australia and over the different seasons of the year. The average peak sun hours were calculated from the Bureau of Meteorology (BOM, 2013) for each study location and presented in Table 5.2.

Table 5.2 Solar electricity produced and GHG emissions saved

	Average Peak Sun hours per day	**Panel Size**	**Average kWh per year**
Regional Processor	6.4	20	46 400
Independent Retailer	5.3	100	193 000
City Processor	5.3	10	19 300

In reality, solar electricity will be used by the entire facility (whether regional processor, independent retailer or city processor) and used for all products. However, as this study aims to mitigate GHG from fish fillet production, the total potential GHG reduction from the solar electricity CPS is credited to fish only, excluding the reality that other products in these facilities (such as prawns) will utilise this energy. This is to ensure the GHG reduction is fully stated in this research, rather than attributed to other products produced at each facility.

Solid fish waste potential as a source of organic matter for biogas production and the growth in biogas plants using fish waste has increased worldwide (Arvanitoyannis and Kassaveti, 2008; Chen et al., 2010; Curry and Pillay, 2012; Gebauer, 2004; Gumisiriza et al., 2009; Kafle et al., 2013; Leitão et al., 2006; Nges et al., 2012; Walekhwa et al., 2014). The utilisation of filleting waste for biogas (a technological modification and recycling waste CPS), provides a second alternative source to grid electricity consumption. Using the Buswell Equation (Symons and Buswell, 1933) (Equation 5.1), the moisture, fat, protein, ash and carbohydrate content (Esteban et al., 2007; Khoddami, 2012) and the amino and fatty acid breakdown of the fish species from Western Australia (Ng, 2010), the CO_2, CH_4, ammonia (NH_3) and hydrogen sulphide (H_2S) from the anaerobic digestion process can be predicted.

$$\begin{aligned} \mathrm{C}_a\mathrm{H}_b\mathrm{O}_c\mathrm{N}_d\mathrm{S}_e &+ \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right)\mathrm{H_2O} \\ &\rightarrow \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{b} + \frac{e}{4}\right)\mathrm{CO_2} + \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right)\mathrm{CH_4} \\ &+ \mathrm{d}\cdot\mathrm{NH_3} + \mathrm{e}\cdot\mathrm{H_2S} \end{aligned} \tag{5.1}$$

Although the Buswell Equation assumes complete digestion, it can be used to predict the quantity of potential CH_4 production. Both Davidsson et al. (2007) and Curry and Pillay (2012) calculated the actual methane yield compared to the predicted yield of municipal waste was 76.7 % and 74.9 % of volatile solids from each author respectively. Therefore, the average of these figures (75.8 % digestion) was applied to this study and presented in Table 5.3.

In reality, biogas electricity will also be used by the entire facility (whether regional processor, independent retailer or city processor) and used for all products. However, as with the solar CPS, this study aims to mitigate GHG from fish fillet production, the total potential GHG reduction from the biogas electricity CPS is credited to fish only. This is to ensure the GHG reduction is fully stated in this research, rather than attributed to other products produced at each facility.

Table 5.3 Results from the Buswell Equation

kg per kg of waste	Carbon dioxide	Methane	Ammonia	Hydrogen sulphide	Water
Amino acids	0.09960	0.0389	0.0216	0.00185	0.0365
Fatty acids	0.0337	0.0282			0.0219
Carbohydrates	0.00170	0.000621			0.000174
Total	**0.1350**	**0.0677**	**0.0216**	**0.00185**	**0.0585**
78.8 % digestion	0.102	0.0513	0.0164	0.00140	0.0443
Per Functional Unit (regional and independent supply chain)	171	85.6	27.3	2.33	74.1
Per Functional Unit (major supply chain)	129	64.9	20.7	1.77	56.1

As methane has an energy density of 55 MJ/kg, this provides 4 760 MJ of energy in a gas format. To convert this to electricity, 56 % of the energy is lost in powering the motor (Reedman, Personal Communication), resulting in a potential 608 kWh, 608 kWh and 461 kWh of electricity from the waste of one metric tonne of fish fillets in the regional, independent and major supply chains respectively (Table 5.4).

Table 5.4 Electricity potential and GHG savings from biogas

	Waste per year (kg)	Potential electricity (kWh per year)
Per Functional Unit (regional and independent supply chain)	1 670	608
Per Functional Unit (major supply chain)	1 260	461
Regional Processor	20 200	7 350
Independent Retailer	13 700	5 000
City Processor	28 600	10 400

5.2.1. Partial life cycle assessment

Goal and scope

The goal was to ascertain the GHG emissions from electricity consumption after variable speed drive installation and substituting electricity for solar and biogas electricity. The functional unit was still one metric tonne of processed fish sold at retail. The system boundaries of this section include the electricity required, filleting waste and the refrigerant as listed below:

Current system

- Grid electricity
- Waste disposal
- Refrigeration gases

Variable speed drive

- Grid electricity
- Waste disposal
- Refrigeration gases

Solar electricity

- Grid electricity consumed
- Electricity produced
- GHG from solar power
- Waste disposal

Biogas electricity

- Grid electricity consumed
- Electricity produced
- Waste reduction

Life cycle inventory

The inputs and outputs required to produce one metric tonne of processed fish fillets with electricity CPSs in the regional processor, independent retailer and city processor are presented in Tables 5.5 - 5.7 .

Table 5.5 Inputs and outputs from electricity CPSs per metric tonne of fish fillets for the Regional Processor

	Units	Current System	Variable Speed Drive	Solar Electricity	Biogas Electricity
Inputs					
Electricity	kWh	8 100	6 479	4 260	7 490
Waste	kg				1 670

	Units	Current System	Variable Speed Drive	Solar Electricity	Biogas Electricity
Outputs					
Fish waste	kg	1 670	1 670	1 670	
Energy	kWh			3 840	608

Table 5.6 Inputs and outputs from electricity CPSs per metric tonne of fish fillets for the Independent Retailer

	Units	Current System	Variable Speed Drive	Solar Electricity	Biogas Electricity
Inputs					
Electricity	kWh	91 500	73 200	68 100	90 900
Waste	kg				1 670
Outputs					
Fish waste	kg	1 670	1 670	1 670	
Energy	kWh			23 400	608

Table 5.7 Inputs and outputs from electricity CPSs per metric tonne of fish fillets for the City Processor

	Units	Current System	Variable Speed Drive	Solar Electricity	Biogas Electricity
Inputs					
Electricity	kWh	1 930	1 550	1 083	1 470
Waste recovered	kg				1 260
Outputs					
Fish waste	kg	1 260	1 260	1 260	
Energy	kWh			852	461

Impact assessment

The impact assessment involved connecting each item in the LCI to the relevant emission factor. The LCI of the regional processor, independent retailer and city processor were multiplied by the respective emission factors and the resulting GHG emissions are presented in Tables 5.8-5.10.

Solar electricity had the highest potential GHG reduction from electricity CPSs for the regional processor, followed by variable speed drives and biogas (Table 5.8).

Table 5.8 GHG emissions from electricity CPSs (kg CO_2 –eq per metric tonne of fish fillets) for the Regional Processor

	Current System	**Variable Speed Drive**	**Solar Electricity**	**Biogas Electricity**
Inputs				
Electricity	7 440	4 450	3 900	6 880
Outputs				
Fish waste	2 310	2 310	2 310	
Solar electricity			288	
Total	**9 750**	**6 760**	**6 500**	**6 880**
Potential GHG reduction		2 990	3 250	2 870

Solar electricity also had the highest potential GHG reduction from electricity CPSs for the independent retailer, followed by variable speed drives and biogas (Table 5.9).

Table 5.9 GHG emissions from electricity CPSs (kg CO_2 –eq per metric tonne of fish fillets) for the Independent Retailer

	Current System	**Variable Speed Drive**	**Solar Electricity**	**Biogas Electricity**
Inputs				
Electricity	84 100	66 000	62 400	83 500
Outputs				
Fish waste	2 310	2 310	2 310	
Solar electricity			1755	
Total	**86 400**	**68 300**	**66 500**	**83 500**
Potential GHG reduction		18 100	19 900	2 870

Biogas electricity had the highest potential GHG reduction from electricity CPSs for the city processor, differing from the regional processer and independent retailer (Table 5.10). Variable speed drives and solar electricity had potential GHG reduction, but less than biogas. This may be the case as the city processor has a more efficient electricity consumption than the regional processor and independent retailer.

Table 5.10 GHG emissions from electricity CPSs (kg CO_2 –eq per metric tonne of fish fillets) for the City Processor

	Current System	**Variable Speed Drive**	**Solar Electricity**	**Biogas Electricity**
Inputs				
Electricity	1 780	1 060	992	1 350
Outputs				
Fish waste	1 750	1 750	1 750	
Solar electricity			64	
Total	**3 530**	**2 820**	**2 810**	**1 350**
Potential GHG reduction		713	721	2 180

Interpretation

Relative impacts from the various CPS are shown in Figure 5.1.

The regional processor would benefit most from solar electricity and variable speed drive installation, with potential GHG reductions of 3,250 kg CO_2 –eq and 2,990 kg CO_2 –eq respectively (30.6 % and 28.1 % of total GHG emissions) per metric tonne of fillets (Figure 5.1). Biogas electricity still potentially reduces the GHG emissions, but not as effectively.

The independent retailer had similar results with potential GHG reductions of 19,900 kg CO_2 –eq and 18,100 kg CO_2 –eq from solar electricity and variable speed drives respectively (22.2 % and 22.2 % of total GHG emissions) per metric tonne of fillets (Figure 5.1). Biogas electricity still potentially reduces the GHG emissions, but not as effectively.

The city processor would benefit most from biogas electricity with a potential GHG reduction of 2,180 kg CO_2 –eq (49.3 % of total GHG emissions) as unlike the regional processor and independent retailer, the city processor had a higher GHG emission from filleting waste than electricity (Figure 5.1). Solar electricity and variable speed drives still potentially reduce the GHG emissions, but not as effectively.

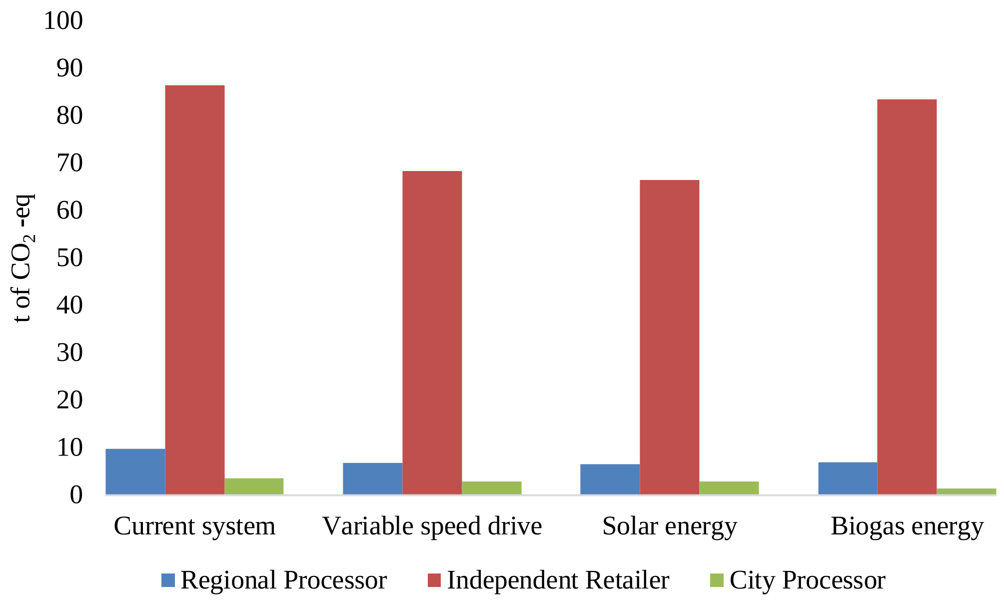

Figure 5.1 GHG emissions from electricity CPS for the Regional Processor, Independent Retailer and City Processor

5.2.2. Economic assessment

The capital and ongoing costs for the electricity CPSs in each facility were calculated and presented in Tables 5.11-5.13. The operating costs displayed are for 2015. The cost benefit analysis includes the waste disposal cost increases until 2019 as taken from Department of Environment Regulation (2014). Costs after this time have been assumed to be in line with inflation.

Table 5.11 Capital and ongoing costs for electricity CPSs for the Regional Processor

CPS	Capital cost	Operating cost per year	Source
Current system			
Electricity		$ 28 356.47	Organisation's power bill
Waste disposal		$ 806.25	(Department of Environment Regulation, 2014)
Total		**$ 29 162.72**	
Variable speed drives			
Variable speed drive	$ 78 000.00		(Office of Environment and Heritage, 2011)
Labour	$ 10 000.00		(Office of Environment and Heritage, 2011)
Engineering	$ 6 000.00		(Office of Environment and Heritage, 2011)
Programming	$ 6 000.00		(Office of Environment and Heritage, 2011)
Electricity		$ 21 550.92	(Food SA, 2013; Synergy, 2014)
Waste disposal		$ 806.25	(Department of Environment Regulation, 2014)
Total	**$ 100 000.00**	**$ 22 357.17**	
Solar electricity			
Panel	$ 20 000.00		(Shetty, Personal Communication)
Government rebate	-$ 11 000.00		(Shetty, Personal Communication)
Electricity		$ 14 953.01	(BOM, 2013; Synergy, 2014)

Waste disposal		$ 806.25	(Department of Environment Regulation, 2014)
Total	**$ 9 000.00**	**$ 15 759.26**	
Biogas electricity			
Stainless steel IBC	$ 2 850.00		Phone call to CCR Plascon 12/9/2014
Generator	$ 11 500.00		(Reedman, Personal Communication)
Maintenance		$ 717.50	Assumed 10 % of capital cost
Electricity		$ 26 233.40	(Synergy, 2014)
Total	**$ 14 350.00**	**$ 26 950.90**	

Table 5.12 Capital and ongoing costs for electricity CPSs for the Independent Retailer

CPS	Capital cost	Operating cost per year	Source
Current system			
Electricity		$ 186 509.05	Organisation’s power bill
Waste disposal		$ 548.69	(Department of Environment Regulation, 2014)
Total		**$ 187 057.74**	
Variable speed drives			
Variable speed drive	$ 78 000.00		(Office of Environment and Heritage, 2011)
Labour	$ 10 000.00		(Office of Environment and Heritage, 2011)

Engineering	$ 6 000.00		(Office of Environment and Heritage, 2011)
Programming	$ 6 000.00		(Office of Environment and Heritage, 2011)
Electricity		$ 1 41 746.88	(Food SA, 2013; Synergy, 2014)
Waste disposal		$ 548.69	(Department of Environment Regulation, 2014)
Total	**$ 100 000.00**	**$ 142 295.57**	
Solar electricity			
Panel	$ 185 000.00		(Shetty, Personal Communication)
Government rebate	-$ 75 000.00		(Shetty, Personal Communication)
Electricity		$ 122 104.22	(BOM, 2013; Synergy, 2014)
Waste disposal		$ 548.69	(Department of Environment Regulation, 2014)
Total	**$ 110 000.00**	**$ 122 652.90**	
Biogas electricity			
Stainless steel IBC	$ 2 850.00		Phone call to CCR Plascon 12/9/2014
Generator	$ 11 500.00		(Reedman, Personal Communication)
Maintenance		$ 717.50	Assumed 10 % of capital cost
Electricity		$ 186 344.40	(Synergy, 2014)
Total	**$ 14 350.00**	**$ 187 061.90**	

Table 5.13 Capital and ongoing costs for electricity CPSs for the City Processor

CPS	Capital cost	Operating cost per year	Source
Current system			
Electricity		$ 29 030.85	Organisation's power bill
Waste disposal		$ 1 144.00	(Department of Environment Regulation, 2014)
Total		**$ 30 174.85**	
Variable speed drives			
Variable speed drive	$ 78 000.00		(Office of Environment and Heritage, 2011)
Labour	$ 10 000.00		(Office of Environment and Heritage, 2011)
Engineering	$ 6 000.00		(Office of Environment and Heritage, 2011)
Programming	$ 6 000.00		(Office of Environment and Heritage, 2011)
Electricity		$ 22 063.45	(Food SA, 2013; Synergy, 2014)
Waste disposal		$ 1 144.00	(Department of Environment Regulation, 2014)
Total	**$ 100 000.00**	**$ 23 207.45**	
Solar electricity			
Panel (includes government rebate)	$ 15 665.00		(Clean Energy Council, 2014)
Electricity		$ 21 895.44	(BOM, 2013; Synergy, 2014)

Waste disposal		$ 1 144.00	(Department of Environment Regulation, 2014)
Total	**$ 15 665.00**	**$ 23 039.44**	
Biogas electricity			
Stainless steel IBC	$ 2 850.00		Phone call to CCR Plascon 12/9/2014
Generator	$ 11 500.00		(Reedman, Personal Communication)
Maintenance		$ 717.50	Assumed 10 % of capital cost
Electricity		$ 25 260.68	(Synergy, 2014)
Total	**$ 14 350.00**	**$ 40 328.18**	

Investment comparison to GHG reduction

The largest GHG savings for the lowest capital cost was calculated in Table 5.14. As the government rebate is received within the year it was included in this calculation. The greatest GHG savings per capital cost for the regional processor and independent retailer was solar electricity, preventing 4.37 kg of CO_2 –eq and 1.49 kg of CO_2 –eq per $ 1 respectively. Biogas electricity can provide the largest GHG reduction from the city processor at 2.31 kg of CO_2 –eq per $ 1.

Table 5.14 GHG mitigated per $ of investment (kg of CO_2 –eq) for electricity CPSs

	Variable speed drive	**Solar electricity**	**Biogas electricity**
Regional Processor	0.335	4.37	1.69
Independent Retailer	1.38	1.49	1.15
City Processor	0.15	1.04	2.31

Cost benefit analysis

The net present value (NPV) of each CPS is compared in Tables 5.15-5.17. This calculation indicates the value and potential profit of the CPS investment after 15 years, taking into account inflation, capital depreciation and revenue. It allows comparison between CPSs to determine the best return on investment over time. A negative value indicates costs are not recovered over this period, whereas a positive value indicates the potential profit over 15 years.

Biogas electricity provided the greatest NPV in 15 years in the regional processor compared to its' current system ($ 195,506.18). Solar electricity also provided a positive year NPV in both the regional and city processors ($ 142,978.31 and $ 65,887.63 respectively), whereas the benefits from variable speed drives would not cover the costs within 15 years.

Solar electricity and variable speed drives provided the greatest NPV for the independent retailer ($ 414,675.88 and $ 404,443.91 respectively). Biogas electricity costs from the independent retailer would not be covered by the benefits within 15 years.

Table 5.15 NPV for electricity CPSs for the Regional Processor

	Current system	Variable speed drive	Solar electricity	Biogas electricity
NPV	-$ 332 921.33	-$ 357 577.85	-$ 189 885.46	-$ 137 357.60
Difference		**-$ 24 656.52**	**$ 142 978.31**	**$ 195 506.18**

Table 5.16 NPV for electricity CPSs for the Independent Retailer

	Current system	Variable speed drive	Solar electricity	Biogas electricity
NPV	-$ 2 117 606.34	-$ 1 713 162.43	-$ 1 105 146.31	-$ 1 525 574.10
Difference		**$ 404 443.91**	**$ 414 675.88**	**-$ 5 751.90**

Table 5.17 NPV for electricity CPSs for the City Processor

	Current system	Variable speed drive	Solar electricity	Biogas electricity
NPV	-$ 347 203.75	-$ 370 030.54	-$ 281 316.12	-$ 307 221.62
Difference		**-$ 22 826.80**	**$ 65 887.63**	**$ 39 982.12**

5.2.3. Quality assessment

Variable speed drives reduce the stress on the refrigeration equipment. Therefore, refrigerators and freezers will be expected to return to, and maintain temperature more effectively, thus conserving or improving the quality of the fish.

Substituting the source of electricity does not affect the product quality in any way as it is still kept in the same conditions.

5.3. Refrigeration gases

Replacing the current refrigeration equipment with low emission refrigerant may reduce the GHG emissions. Equipment with R134a refrigerant has been investigated. A walk in freezer utilising R134a could not be found for the city processer. Instead, the analysis uses chest freezers.

5.3.1. Partial life cycle assessment

Goal and scope

The goal was to ascertain the GHG emissions from replacing the refrigeration equipment. The functional unit was still one metric tonne of processed fish sold at retail. The system boundaries of this section include the electricity required and the refrigerant as listed below:

Current system

- Grid electricity
- Refrigeration gases

New refrigeration system

- Grid electricity
- Refrigeration gases

Life cycle inventory

The inputs and outputs required to produce one metric tonne of processed fish fillets with refrigeration CPSs in the regional processor, independent retailer and city processor are presented in Tables 5.18-5.20.

Table 5.18 Inputs and outputs from refrigeration CPSs per metric tonne of fish fillets for the Regional Processor

	Units	Current System	R134 System
Inputs			
Electricity	kWh	8 100	7 850
Outputs			
R404a refrigerant	kg	0.948	
R134a refrigerant	kg		0.948

Table 5.19 Inputs and outputs from refrigeration CPSs per metric tonne of fish fillets for the Independent Retailer

	Units	Current System	R134 System
Inputs			
Electricity	kWh	91 500	89 900
Outputs			
R404a refrigerant	kg	7.84	
R134a refrigerant	kg		7.84

Table 5.20 Inputs and outputs from refrigeration CPSs per metric tonne of fish fillets for the City Processor

	Units	Current System	R134 System
Inputs			
Electricity	kWh	1 930	3 750
Outputs			
R404a refrigerant	kg	0.796	
R134a refrigerant	kg		0.796

Impact assessment

The impact assessment involved connecting each item in the LCI to the relevant emission factor. The LCI of the regional processor, independent retailer and city processor were multiplied by the respective emission factors and the resulting GHG emissions are presented in Tables 5.21-5.23.

Table 5.21 GHG emissions from refrigeration CPSs (kg CO_2 –eq per metric tonne of fish fillets) from the Regional Processor

	Current System	**R134 System**
Inputs		
Electricity	7 440	7 210
Outputs		
R404a refrigerant	386	
R134a refrigerant		154
Total	**7 830**	**7 370**
Potential GHG reduction		458

Table 5.22 GHG emissions from refrigeration CPSs (kg CO_2 –eq per metric tonne of fish fillets) from the Independent Retailer

	Current System	**R134 System**
Inputs		
Electricity	84 100	82 600
Outputs		
R404a refrigerant	3 190	
R134a refrigerant		1 270
Total	**87 300**	**83 900**
Potential GHG reduction		3 380

Table 5.23 GHG emissions from refrigeration CPSs (kg CO_2 –eq per metric tonne of fish fillets) from the City Processor

	Current System	**R134 System**
Inputs		
Electricity	1 780	1 720
Outputs		
R404a refrigerant	324	
R134a refrigerant		129

Total	**2 100**	**1 850**
Potential GHG reduction		249

Interpretation

Replacing the refrigeration equipment with R134a system will reduce the GHG emissions (Figure 5.2). As the independent retailer had more equipment that needed a larger quantity of refrigerant per metric tonne of fillets, it also had the opportunity for the greatest GHG reduction.

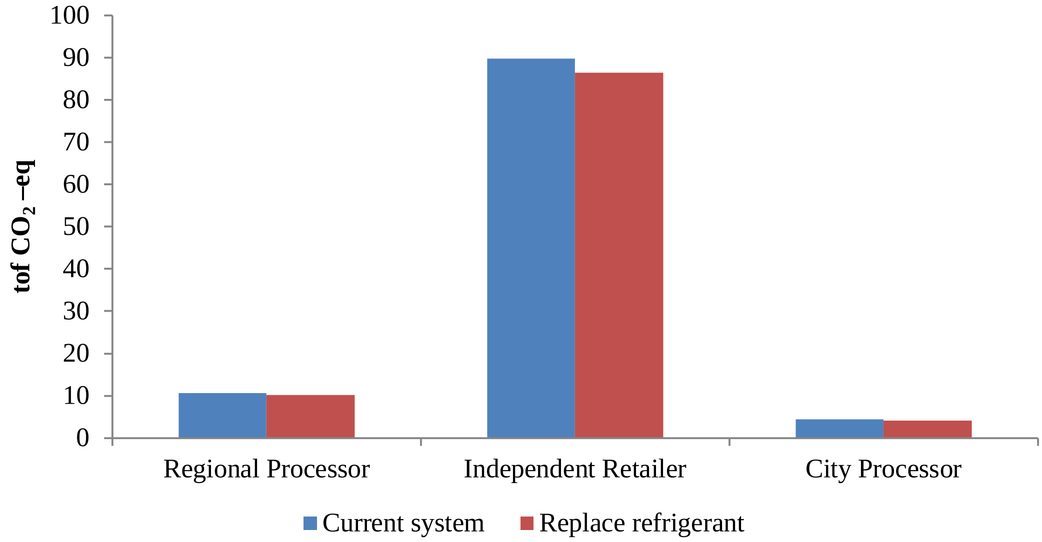

Figure 5.2 GHG emissions from replacing the refrigerant CPS

5.3.2. <u>Economic assessment</u>

The capital and ongoing costs for the refrigeration CPSs in each facility were calculated and presented in Tables 5.24-5.26. The operating costs displayed are for 2015. Leasing equipment is not an option for the regional processor as lease companies do not have the capacity to maintain the equipment in the remote location. The regional processor currently uses the cool room built into the premises they rent.

Table 5.24 Capital and ongoing costs for refrigeration CPSs for the Regional Processor

CPS	Capital cost	Operating cost per year	Source
Current system			
Electricity		$ 28 356.47	Organisation's power bill
Refrigeration gas		$ 902.12	(Thermo Fisher Scientific, 2015)
Total	**$ 0.00**	**$ 29 258.60**	
Replace refrigerant			
New system	$ 2 880.90		(Premier Rentals, 2013)
Shipping	$ 96.96		(Freight Calculator Australia, 2015)
Installation	$ 288.09		Assumed 10 % of capital costs
Electricity		$ 27 494.44	(Premier Rentals, 2013; Synergy, 2014)
Refrigeration gas		$ 246.01	(Thermo Fisher Scientific, 2015)
Total	**$ 3 265.95**	**$ 27 740.45**	

Table 5.25 Capital and ongoing costs for refrigeration CPSs for the Independent Retailer

CPS	Capital cost	Operating cost per year	
Current system			
Electricity		$ 186 509.05	Organisation's power bill

Lease		$ 20 320.56	(Premier Rentals, 2013)
Total	**$ 0.00**	**$ 206 829.61**	
Replace refrigerant			
Lease		$ 8 997.56	(Premier Rentals, 2013)
Electricity		$ 103 150.67	(Premier Rentals, 2013; Synergy, 2014)
Total	**$ 0.00**	**$ 112 148.23**	

Table 5.26 Capital and ongoing costs for refrigeration CPSs for the City Processor

CPS	Capital cost	Operating cost per year	
Current system			
Electricity		$ 29 030.85	Organisation's power bill
Refrigeration gas		$ 1 250.00	(Thermo Fisher Scientific, 2015)
Total	**$ 0.00**	**$ 30 280.85**	
Replace refrigerant			
New system	5 x $ 13 279.20		(Premier Rentals, 2013)
Electricity		$ 28 148.31	(Premier Rentals, 2013; Synergy, 2014)
Refrigeration gas		$ 746.98	(Thermo Fisher Scientific, 2015)
Total	**$ 66 396.00**	**$ 28 895.29**	

Investment comparison to GHG reduction

Investing in a new refrigeration system will potentially mitigate 1.697 and 0.085 kg of CO_2 –eq per dollar invested in the regional and city processors respectively (Table 5.27). The independent retailer did not require capital investment as they lease their equipment.

Table 5.27 GHG mitigated per $ of investment (kg of CO_2 –eq) for electricity CPSs

	R134 System
Regional Processor	1.697
Independent Retailer	N/A[a]
City Processor	0.085

[a] No capital investment is required

Cost benefit analysis

The NPV from the refrigeration replacement CPS is compared in Tables 5.28-5.30. This calculation indicates the value and potential profit of the CPS investment after 15 years, taking into account inflation, capital depreciation and revenue. It allows comparison between CPSs to determine the best return on investment over time. A negative value indicates costs are not recovered over this period, whereas a positive value indicates the potential profit over 15 years. Replacing the equipment has a $ 86,166.33, $ 1,070,375.18 and $ 35,395.50 NPV difference for the regional processor, independent retailer and city processor respectively. The independent retailer had a higher NPV difference as the equipment lease is cheaper than the current system.

Table 5.28 NPV for refrigeration gas CPSs for the Regional Processor

	Current system	**R134 System**
NPV	-$ 330 769.10	-$ 244 602.77
Difference		**$ 86 166.33**

Table 5.29 NPV for refrigeration gas CPSs for the Independent Retailer

	Current system	**R134 System**
NPV	-$ 2 338 213.39	-$ 1 267 838.21
Difference		**$ 1 070 375.18**

Table 5.30 NPV for refrigeration gas CPSs for the City Processor

	Current system	**R134 System**
NPV	-$ 341 620.98	-$ 306 225.48
Difference		**$ 35 395.50**

5.3.1. Quality assessment

Refrigerant substitution reduce the stress on the refrigeration equipment. Therefore, refrigerators and freezers will be expected to return to, and maintain temperature more effectively, thus conserving or improving the quality of the fish.

5.4. Recycling filleting waste

As up to 62.5 % of the whole fish is disposed in landfill, there is an opportunity to create new products from the waste. Therefore, the recycling opportunities investigated were hydrolysate, dried waste and mince extraction.

The mince extractor separates flesh from bone after filleting, providing a fish mince otherwise disposed of. This mince can then be used in burgers and surimi like products. The heads, bones and guts are unaltered, left for landfill.

The hydrolysate process involves treating the waste with formic acid and mixing it to break carbohydrates into sugars, lipids into fatty acids and proteins into amino acids (Hall, 2011a). After this process a shelf stable liquid is formed that is then packaged and sold as organic fertiliser to local farms.

The dryer works as a vacuum, allowing evaporation at ambient temperature. Thus, the product is not cooked in the process, maintaining the protein structure, but instead has the liquid drawn out (Howieson et al., 2013). Use of this provides a product with an extended shelf life, either in the original or agitated shape, and a liquid product.

5.4.1. Partial life cycle assessment

Goal and scope

The goal was to ascertain the GHG emissions from electricity substitution from recycling waste in the regional processor, independent retailer and city processor facilities compared to waste disposal and landfill emissions. The functional unit was still one metric tonne of processed fish sold at retail. As hydrolysate production displaces fertiliser, the equivalent quantity of urea ammonium nitrate, potassium chloride and single superphosphate are included. However, as mincing and drying created new products, no GHG data was available for displacement providing a limitation in this study.

The system boundaries of this section include:

Current system
- Waste disposal

Mincing
- Waste recycled
- Waste disposal
- Energy
- Consumable items
- New product

Hydrolysate
- Waste recycled
- Energy
- Consumable items
- New product
- Fertiliser displacement

Dried product
- Waste recycled
- Energy
- Consumable items
- New product

Life cycle inventory

The inputs and outputs required to recycle the waste from one metric tonne of processed fish fillets in the regional processor, independent retailer and city processor are presented in Table 5.31 as a LCI.

Table 5.31 Inputs, outputs and displacement from recycling filleting waste CPSs per metric tonne of fish fillets for the Regional Processor and Independent Retailer

	Unit	Current System	Mince Extraction	Hydrolysate	Dryer
Inputs					
Fish waste	kg		1 670	1 670	1 670
Electricity	kWh		20	1 560	42 100
Water	kg		1 330	87 900	24 600

Detergent	kg		0.67	8.77	24.6
Gas	MJ			32 500	
Formic acid	kg			33.3	
Outputs					
Fish waste	kg	1 670	1 270		
Extracted mince	kg		397		
Hydrolysate	kg			1 670	
Dried product	kg				574
Liquid	L				1 110
Displacement					
Urea ammonium nitrate	kg of N			-161	
Potassium chloride	kg of K			-9.44	
Single superphosphate	kg of P			-27	

Table 5.32 Inputs, outputs and displacement from filleting waste CPSs per metric tonne of fish fillets for the City Processor

	Unit	**Current System**	**Mince Extraction**	**Hydrolysate**	**Dryer**
Inputs					
Fish waste	kg		1 260	1 260	1 260
Electricity	kWh		15.2	1 150	32 000
Water	kg		1 010	66 700	18 700
Detergent	kg		0.51	6.65	18.7
Gas	MJ			24 700	
Formic acid	kg			25.3	
Outputs					
Fish waste	kg	1 260	963		
Extracted mince	kg		301		
Hydrolysate fertiliser	kg			1 260	
Dried product	kg				435
Liquid	L				841

Displacement			
Urea ammonium nitrate	kg of N		-122
Potassium chloride	kg of K		-7.16
Single superphosphate	kg of P		-20.5

Impact assessment

The impact assessment involved connecting each item in the LCI to the relevant emission factor. The LCI of the regional processor, independent retailer and city processor were multiplied by the respective emission factors and the resulting GHG emissions are presented in Tables 5.33 and 5.34.

Table 5.33 GHG emissions from recycling filleting waste CPSs (kg CO_2 –eq per metric tonne of fish fillets) for the Regional Processor and Independent Retailer

	Current System	**Mince Extraction**	**Hydrolysate**	**Dryer**
Inputs				
Detergent		0.346	4.56	12.8
Electricity		18.4	1 400	38 700
Formic acid			35.8	
Gas			1 900	
Water		0.423	27.9	7.82
Outputs				
Fish waste	2 310	1 760		
Total	**2 310**	**1 780**	**3 360**	**38 700**
Potential GHG reduction		532	-1 050	-36 400
Displacement				
Potassium chloride			20.2	
Single superphosphate			0.0901	
Urea ammonium nitrate			1 030	
Total			**1 050**	
Total - Displacement	**2 310**	**1 780**	**2 310**	**38 700**

Potential GHG reduction		532	-4.6	-36 400

Table 5.34 GHG emissions from recycling filleting waste CPSs (kg CO_2 –eq per metric tonne of fish fillets) for the City Processor

	Current System	**Mince Extraction**	**Hydrolysate**	**Dryer**
Inputs				
Detergent		0.263	3.46	9.71
Electricity		13.9	1 060	29 400
Formic acid			27.2	
Gas			1 440	
Water		0.321	21.2	5.93
Outputs				
Fish waste	1 750	1 330		
Total GHG emissions	**1 750**	**1 350**	**2 550**	**29 400**
Potential GHG reduction		403	-1 050	-27 600
Product displacement				
Urea ammonium nitrate			780	
Potassium chloride			15.3	
Single superphosphate			0.0683	
Total			**795**	
Total - Displacement	**1 750**	**1 350**	**1 760**	**29 400**
Potential GHG reduction		403	-3.50	-27 600

Interpretation

Relative impacts from the various CPS are shown in Figure 5.3. As the results are relative to the quantity of waste, results do not differ in percentage of waste between sectors. Therefore, results are discussed by CPS.

Drying the fish waste resulted in 16.8 times the GHG emissions from landfill in all sectors, due to the high electricity consumption. The dryer selected was a laboratory based sized, with a maximum capacity of 50 kg of product per day. Whilst this is the first of its' kind in Australia, an industrial sized dryer may be more efficient per metric tonne of waste dried.

Hydrolysate production emitted a similar GHG emissions to landfill after synthetic fertiliser displacement. So, for the amount of urea ammonium nitrate, single superphosphate and potassium chloride displaced in the process, fish waste hydrolysate still had more emissions than fish waste in landfill. Gas and electricity were the areas of greatest impact in this process. Gas was used for operating the forklift and heating, and electricity used in the agitator and sieve.

The mincer had the lowest GHG emissions in all sectors (78 % of the current system). Mincing still required landfill, but reduced the current waste by 22.8 %.

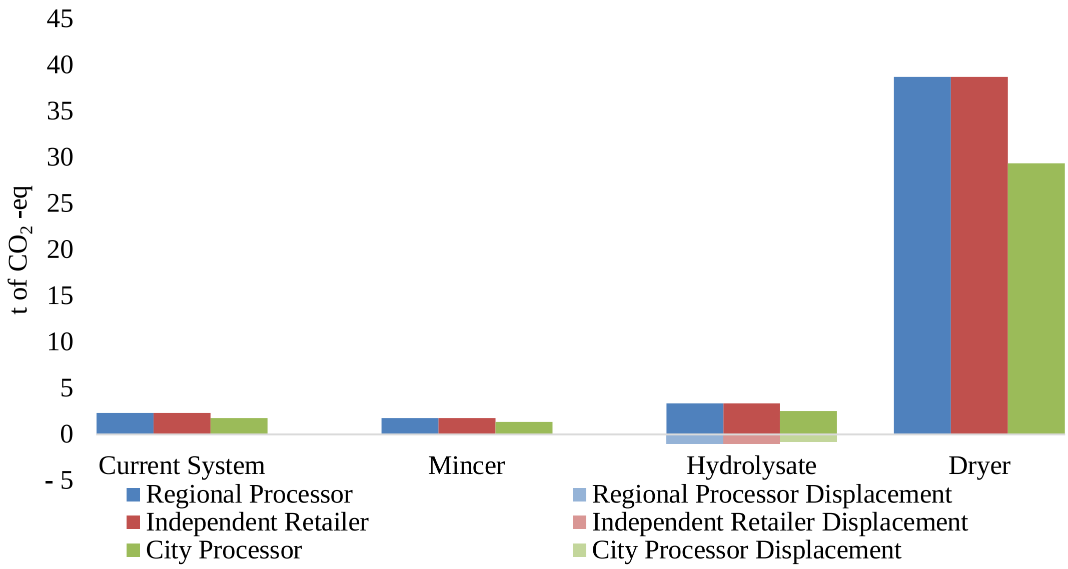

Figure 5.3 GHG emissions from recycling filleting waste [a]

[a] No GHG emission data was available for the new products created from mincing and drying displacement.

5.4.2. Economic assessment

The capital and ongoing costs for the recycling CPSs in each facility were calculated and presented in Tables 5.35-5.37. The operating costs displayed are for 2015. The cost benefit analysis includes the waste disposal cost increases until 2019 as taken from Department of Environment Regulation (2014). Costs after this time have been assumed to be in line with inflation.

Table 5.35 Capital and ongoing costs for recycling CPSs for the Regional Processor

CPS	Capital cost	Operating cost per year	Revenue per year	Source
Current system				
Waste disposal		$ 806.25		(Department of Environment Regulation, 2014)
Total		**$ 806.25**		
Mince extraction				
Machinery	$ 250 000.00			Phone call to SARDI 4/3/2014
Electricity		$ 7 094.36		Phone call to SARDI 4/3/2014
Water		$ 37.41		Phone call to SARDI 4/3/2014
Landfill levy		$ 614.02		(Department of Environment Regulation, 2014)
Labour cost at $ 25/hr		$ 1 441.73		(Boulter and Bremner, n.d.)
Packaging		$ 961.15		(Boulter and Bremner, n.d.)
Sale at $ 2 per kg			$ 9 611.51	Industry estimate
Total	**$ 250 000.00**	**$ 60 148.67**	**$ 9 611.51**	

Hydrolysate				
Machinery	$ 350 000.00			Industry email
Electricity		$ 7 073.78		Industry email and (Synergy, 2014)
Acid		$ 12 416.25		(Thermo Fisher Scientific, 2015)
Gas		$ 30 492.16		Industry email
Water		$ 3 433.99		Industry email
Labour cost at $ 25/hr		$ 50 000.00		(Boulter and Bremner, n.d.)
Sale at $ 9.88 per kg			$ 199 143.75	(Bunnings, 2014)
Total	**$ 350 000.00**	**$ 103 416.18**	**$ 199 143.75**	
Dryer				
Machinery	$ 75 000.00			Quote from Janet Howieson
Electricity		$ 179 245.34		(Howieson et al., 2013; Synergy, 2014)
Water		$ 81.19		(Howieson et al., 2013; Water Corporation, 2013)
Labour cost at $ 25/hr		$ 50 000.00		(Boulter and Bremner, n.d.)
Sale at $ 1.96 per kg			$ 39 600.26	(Index mundi, 2014)
Total	**$ 75 000.00**	**$ 229 326.53**	**$ 39 600.26**	

Table 5.36 Capital and ongoing costs for recycling CPSs for the Independent Retailer

CPS	Capital cost	Operating cost per year	Revenue per year	Source
Current system				
Waste disposal		$ 548.69		(Department of Environment Regulation, 2014)
Total		**$ 548.69**		
Mince extraction				
Machinery	$ 250 000.00			Phone call to SARDI 4/3/2014
Electricity		$ 4 828.03		Phone call to SARDI 4/3/2014
Water		$ 40.58		Phone call to SARDI 4/3/2014
Landfill levy		$ 417.87		(Department of Environment Regulation, 2014)
Labour cost at $ 25/hr		$ 981.16		(Boulter and Bremner, n.d.)
Packaging		$ 654.11		(Boulter and Bremner, n.d.)
Sale at $ 2 per kg			$ 8 306.10	Industry estimate
Total	**$ 250 000.00**	**$ 6 921.75**	**$ 8 306.10**	
Hydrolysate				
Machinery	$ 350 000.00			Industry email
Electricity		$ 4 814.03		Industry email and (Synergy, 2014)
Acid		$ 8 449.82		(Thermo Fisher Scientific, 2015)

Gas		$ 20 751.30		Industry email
Water		$ 2 336.98		Industry email
Labour cost at $ 25/hr		$ 50 000.00		(Boulter and Bremner, n.d.)
Sale at $ 9.88 per kg			$ 135 526.34	(Bunnings, 2014)
Total	**$ 350 000.00**	**$ 86 352.13**	**$ 135 526.34**	
Dryer				
Machinery	$ 75 000.00			Quote from Janet Howieson
Electricity		$ 128 291.18		(Howieson et al., 2013; Synergy, 2014)
Water		$ 55.25		(Howieson et al., 2013; Water Corporation, 2013)
Labour cost at $ 25/hr		$ 50 000.00		(Boulter and Bremner, n.d.)
Sale at $ 1.96 per kg			$ 26 949.77	(Index mundi, 2014)
Total	**$ 75 000.00**	**$ 178 346.44**	**$ 26 949.77**	

Table 5.37 Capital and ongoing costs for recycling CPSs for the City Processor

CPS	Capital cost	Operating cost per year	Revenue per year	Source
Current system				
Waste disposal		$ 1 144.00		(Department of Environment Regulation, 2014)
Total		**$ 1 144.00**		
Mince extraction				
Machinery	$ 250 000.00			Phone call to SARDI 4/3/2014
Electricity		$ 10 066.29		Phone call to SARDI 4/3/2014
Water		$ 53.08		Phone call to SARDI 4/3/2014
Landfill levy		$ 871.24		(Department of Environment Regulation, 2014)
Labour cost at $ 25/hr		$ 2 045.69		(Boulter and Bremner, n.d.)
Packaging		$ 1 363.79		(Boulter and Bremner, n.d.)
Sale at $ 2 per kg			$ 13 637.91	Industry estimate
Total	**$ 250 000.00**	**$ 14 400.09**	**$ 13 637.91**	
Hydrolysate				
Machinery	$ 350 000.00			Industry email
Electricity		$ 43 265.78		Industry email and Synergy (2014)
Acid		$ 17 617.60		(Thermo Fisher Scientific, 2015)

Gas		$ 10 037.09		Industry email
Water		$ 4 872.54		Industry email
Labour cost at $ 25/hr		$ 50 000.00		(Boulter and Bremner, n.d.)
Sale at $ 9.88 per kg			$ 282 568.00	(Bunnings, 2014)
Total	**$ 350 000.00**	**$ 125 793.01**	**$ 282 568.00**	
Dryer				
Machinery	$ 75 000.00			Quote from Janet Howieson
Electricity		$ 254 333.85		(Howieson et al., 2013; Synergy, 2014)
Water		$ 115.20		(Howieson et al., 2013; Water Corporation, 2013)
Labour cost at $ 25/hr		$ 50 000.00		(Boulter and Bremner, n.d.)
Sale at $ 1.96 per kg			$ 56 189.40	(Index mundi, 2014)
Total	**$ 75 000.00**	**$ 304 449.05**	**$ 56 189.40**	

Investment comparison to GHG reduction

The GHG mitigated per dollar of investment (kg of CO_2 –eq) are presented in Table 5.38. As both hydrolysate and drying increase the GHG emissions in all sectors, they have a negative GHG result. Mincing provided the largest GHG reduction per dollar of capital investment

Table 5.38 GHG mitigated per $ of investment (kg of CO_2 –eq) for recycling filleting waste CPSs

	Mincing	**Hydrolysate**	**Drying**
Regional Processor	0.015	-0.033	-6.025
Independent Retailer	0.01	-0.022	-4.1
City Processor	0.021	-0.046	-8.539

Cost benefit analysis

The cost benefit analysis is presented in Tables 5.39-5.41. Mincing and drying the waste could not recover the capital costs in fifteen years in all sectors. Hydrolysate recovered costs and provided a $ 764,364.34, $ 234,844.21 and $ 1,461,165.40 NPV from the current system in the regional processor, independent retailer and city processor respectively.

Table 5.39 NPV for recycling filleting waste CPSs for the Regional Processor

	Current System	**Mincing**	**Hydrolysate**	**Drying**
NPV	-$ 12 350.76	-$ 244 386.16	$ 752 013.58	-$ 2 215 614.35
Difference		-$ 232 035.40	$ 764 364.34	-$ 2 203 263.59

Table 5.40 NPV for recycling filleting waste CPSs for the Independent Retailer

	Current System	**Mincing**	**Hydrolysate**	**Drying**
NPV	-$ 9 117.33	-$ 222 418.47	$ 225 726.87	-$ 1 782 297.38
Difference		-$ 213 301.14	$ 234 844.21	-$ 1 773 180.04

Table 5.41 NPV for recycling filleting waste CPSs for the City Processor

	Current System	Mincing	Hydrolysate	Drying
NPV	-$ 19 009.34	-$ 249 093.16	$ 1 442 156.06	-$ 2 877 335.62
Difference		-$ 230 083.82	$ 1 461 165.40	-$ 2 858 326.28

5.4.3. Quality assessment

Recycling does not affect the original final fish fillet as it is removed during filleting. However, if the waste product is designed for human consumption, it requires food safe handling according to HACCP and the respective quality management system, adding a further cost to production.

5.5. Fillet packaging

Fillet packaging in polystyrene eskies had the largest GHG emission relative to other consumable items purchased. Therefore, as Chapter 4 indicated polystyrene eskies had a larger GHG emission per metric tonne of fish fillets than cardboard boxes, the two are compared further for the regional processor. Figure 5.4 shows the difference in insulation between a cardboard box and air gap box. All options assessed were assumed to be a single use product (consistent with polystyrene esky use) and lined with a carton liner. As the carton liner quantities do not change between these CPSs, they were not included in this analysis.

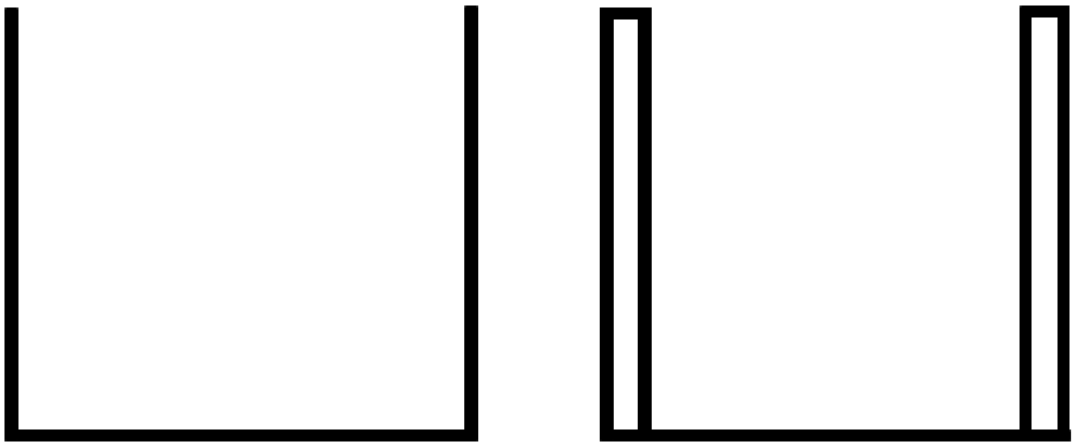

Figure 5.4 Difference between plain cardboard box (left) and air gap box (right)

5.5.1. Partial life cycle assessment

Goal and scope

The goal was to ascertain the GHG emissions from packaging fish fillets in cardboard boxes in comparison to polystyrene eskies. The functional unit was still one metric tonne of processed fish sold at retail. The system boundaries of this section include:

Polystyrene esky	Cardboard boxes
• Polystyrene esky	• Cardboard box

Life cycle inventory

The inputs required to produce one metric tonne of processed fish fillets and package them in the regional processor and city processor are presented in Table 5.42. There were no outputs.

Table 5.42 Inputs from fillet packaging CPSs per metric tonne of fish fillets in the Regional Processor

Polystyrene esky	Cardboard box	Cardboard box with air gap
47.43 kg	94.86 kg	99.6 kg

Impact assessment

The impact assessment involved connecting each item in the LCI to the relevant emission factor. The LCI was multiplied by the respective emission factors to determine the total GHG emissions from each sector measured. The LCI of the regional processor were multiplied by the respective emission factors and the resulting GHG emissions are presented in Table 5.43.

Table 5.43 GHG emissions from fillet packaging CPSs (kg CO_2 –eq per metric tonne of fish fillets) for the Regional Processor

	Current system	Cardboard Box	Cardboard box with air gap
Polystyrene	304.18		
Cardboard		79.27	83.23
Total	**304.18**	**79.27**	**83.23**
Potential GHG reduction		224.91	220.95

Interpretation

Cardboard boxes of have the potential to reduce current GHG emissions for the regional processor (Figure 5.5).

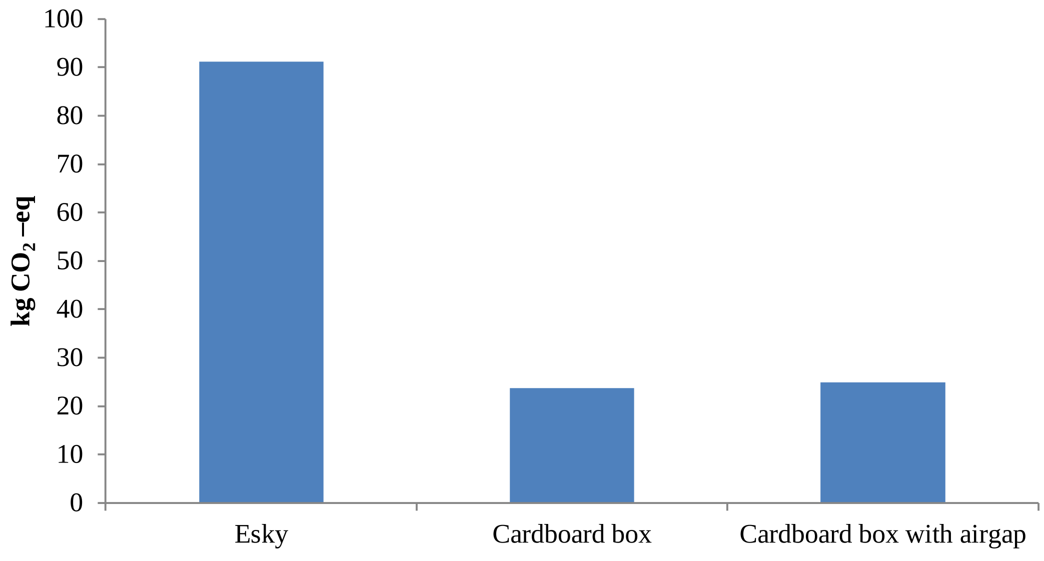

Figure 5.5 GHG emissions from fillet packaging

5.5.2. Economic assessment

The capital and ongoing costs for the filet packaging CPSs in the regional processor was calculated and presented in Table 5.44. The operating costs are displayed are for 2015.

Table 5.44 Capital and ongoing costs for fillet packaging CPSs for the Regional Processor

CPS	Capital cost	Operating cost per year	Source
Current system			
Small polystyrene esky	None	$ 7 739.53	Regional Processor
Large polystyrene esky	None	$ 352.03	Regional Processor
Transport		$ 12.33	Regional Processor
Total		**$ 8 103.90**	
Cardboard boxes			
Small cardboard box	None	$ 5 443.20	(Vital Packaging, 2015)
Large cardboard box	None	$ 2 507.76	(Vital Packaging, 2015)
Transport		$ 24.66	Regional Processor
Total		**$ 7 975.62**	
Cardboard boxes with air gap			
Small cardboard box	None	$ 8 706.98	(Vital Packaging, 2015)

Large cardboard box	None	$ 352.03	(Vital Packaging, 2015)
Transport		$ 24.66	Regional Processor
Total		**$ 9 083.67**	

Investment comparison to GHG reduction

This analysis cannot be calculated as there is no capital investment in changing from polystyrene eskies to carbon footprint.

Cost benefit analysis

The cost benefit analysis is presented in Table 5.45. Changing to plain cardboard boxes provides a potential long term profit (-$ 90,164.59 NPV with a difference of $ 1,450.13) compared to using polystyrene eskies (-$ 91,614.72 NPV) for the regional processor. The cardboard boxes with an air gap were more expensive (-$ 102,691.08 NPV with a -$ 11,076.36 difference).

Table 5.45 NPV for fillet packaging CPSs for the Regional Processor

	Current System	**Cardboard box**	**Cardboard box with air gap**
NPV	-$ 91 614.72	-$ 90 164.59	-$ 102 691.08
Difference		$ 1 450.13	-$ 11 076.36

5.5.3. Quality assessment

Saddletail snapper (*Lutjanus malabaricus*) fillets were split into three groups for testing. Fish were filleted and packed into six lots of 2 kg packs lined with a carton liner with an ice block (like the regional processor). Fillets were not vacuum packed, but placed in the following cartons:

- Polystyrene esky
- Cardboard box with air gap
- Cardboard box without air gap

Cartons were then exposed to a refrigerated environment for three days and assessed for temperature, drip loss, quality index, microbiology and texture differences. A refrigerated environment was used to model the regional processor’s practises and to keep with the Food Standards Code temperature control of “5 °C or below… or 60 °C or above” (FSANZ, 2014b).

Temperature

The fillet and refrigerator temperatures (Figure 5.6) showed the cardboard and air gap box samples had a lower temperature than the polystyrene esky samples. The differences seen between the packaging options may be caused by the position in the refrigerator.

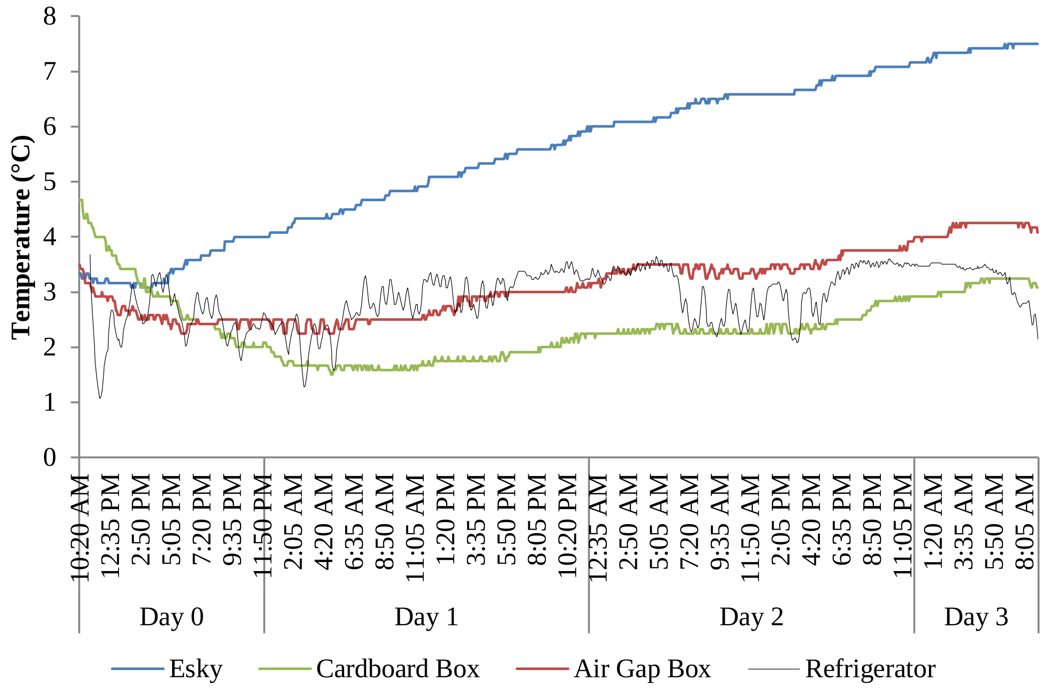

Figure 5.6 Fillet temperature from each packaging CPS

Drip loss

The drip loss did not differ between the three packaging methods over the three days storage time (Figure 5.7). This indicates a 0.79 %, 0.81 % and 0.51 % loss during storage from the polystyrene, plain box and air gap box respectively, indicating a very small difference between the three packages.

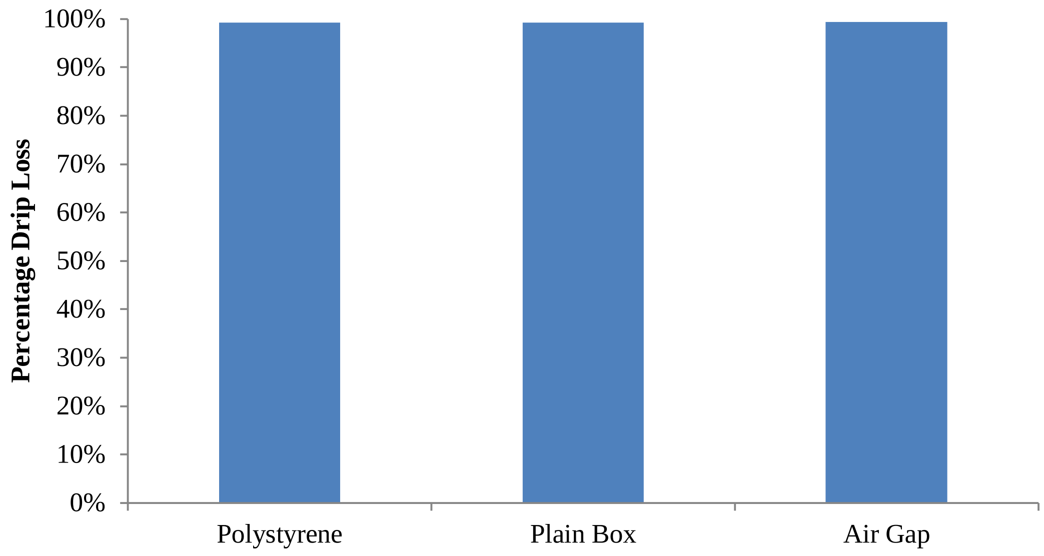

Figure 5.7 Drip loss from each packaging CPS

Quality index

The quality index of stored fillets did not differ between the three packaging methods over the three days storage time (Figure 5.8)

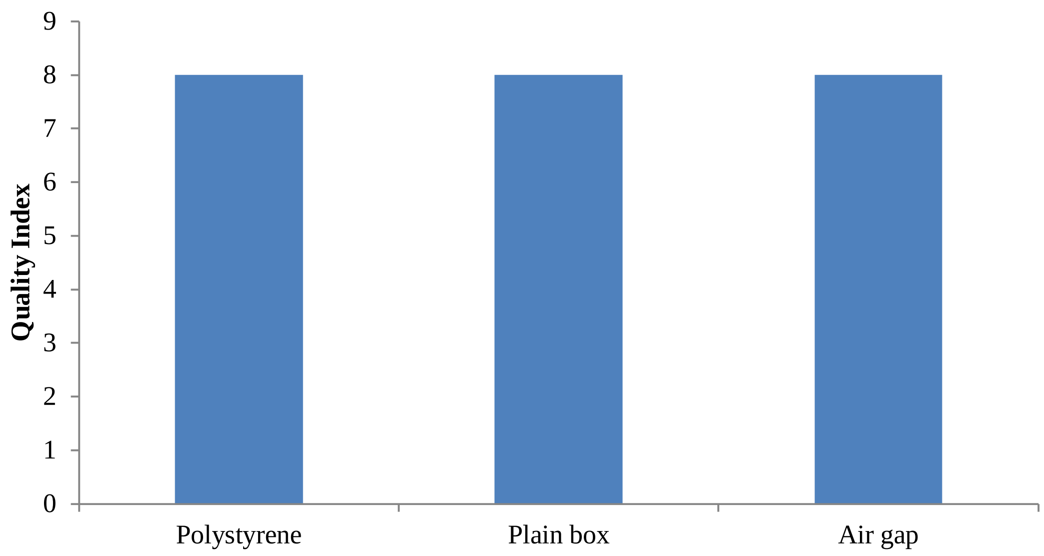

Figure 5.8 Quality index of fillets from each packaging CPS

Microbiology

After three days all samples had a higher total plate count than the recommended 10^6 CFU/g (Sydney Fish Market, 2013) (Figure 5.9). One reason for these high results is the high initial total plate count average of 693,333 CFU/g before the trial started. Whilst this was still below the 10^6 CFU/g recommendation, the high initial count indicated the fillets should be consumed as soon as possible before the 10^6 CFU/g was reached, rather than held in a temperature trial for another three days. Consequently, the fillets sampled had a short remaining shelf life before the trial commenced.

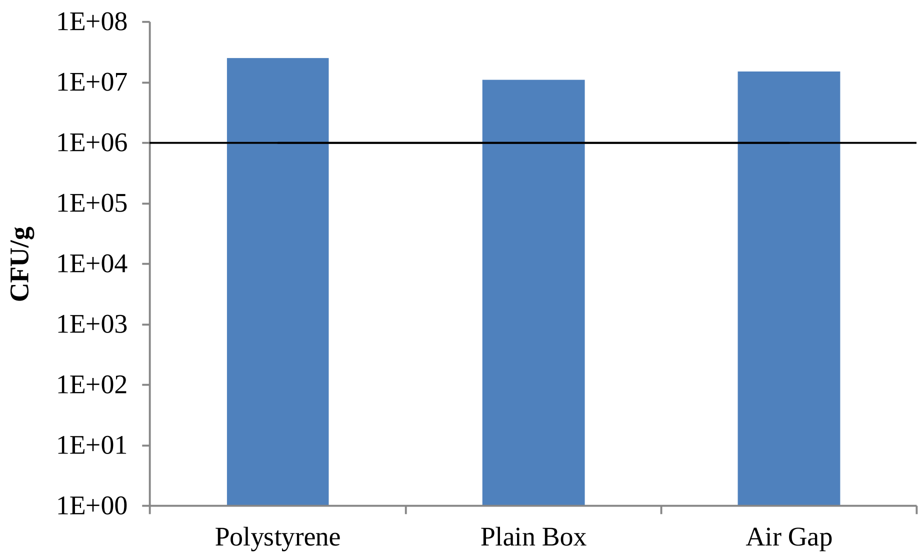

Figure 5.9 Microbiology results from temperature trial of each packaging CPS (line shows recommendation by Sydney Fish Market (2013)

Texture

The hardness and springiness means are presented in Figures 5.10 and 5.11 respectively. Whilst it appeared storage in polystyrene maintained hardness and springiness, results were not consistent, providing a high standard deviation within samples. Thus no conclusion on the texture can be drawn.

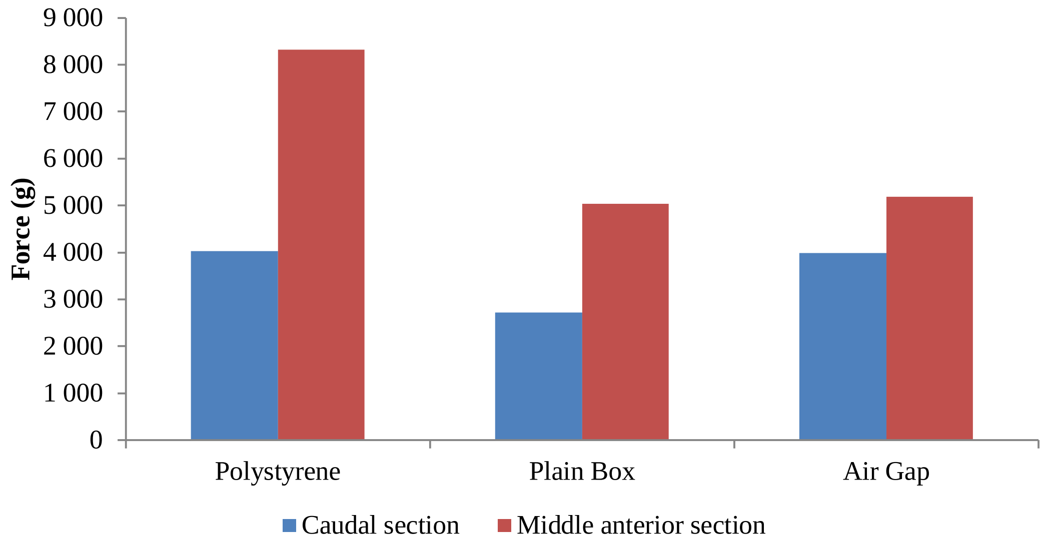

Figure 5.10 Fillet hardness from temperature trial

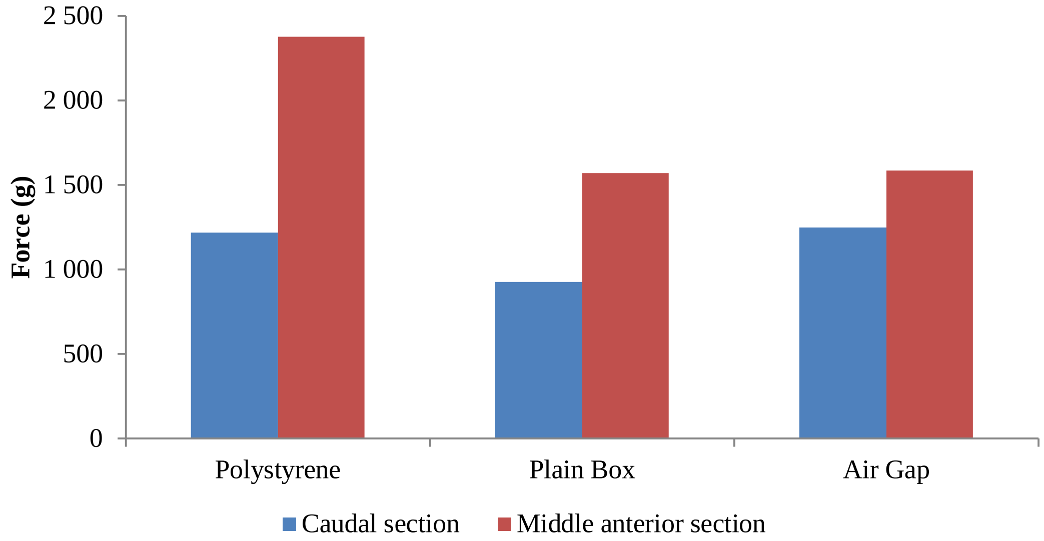

Figure 5.11 Fillet springiness from temperature trial

Quality summary

Overall, there was very little difference in product quality between fillets stored in polystyrene, plain boxes or air gap boxes.

5.6. Cleaner production strategy comparison

5.6.1. Partial life cycle assessment

The total GHG reduction from each CPS in the three sectors measured are presented in Figure 5.12.

Solar electricity had the greatest potential GHG reduction in the regional processor and independent retailer saving a potential 3,249 and 19,904 kg of CO_2 –eq respectively. Although solar also potentially reduced GHG emissions in the city processor (721 kg of CO_2 –eq), biogas provided a greater opportunity (1,200 kg of CO_2 –eq). Variable speed drives also had a potential GHG saving of 2,987, 18,092 and 713 kg of CO_2 –eq in the regional processor, independent retailer and city processor respectively.

5.6.2. Economic assessment

Investment comparison to GHG reduction

A summary of the GHG mitigated per $ of investment (kg of CO_2 –eq) from each CPS is presented in Tables 5.46-5.48.

The most effective CPSs for the lowest capital cost for the regional processor, independent retailer and city processor was solar power, potentially mitigating 9.97, 1.47 and 2.51 kg of CO_2 –eq per $ 1 of investment respectively. This was followed by biogas (6.25, 1.09 and 2.28 kg of CO_2 –eq per $ 1 of investment in the regional processor and independent retailer respectively). As the independent retailer leases their refrigeration equipment, it did not require capital investment. Variable speed drives, replacing refrigeration equipment (in the regional and city processor) and recycling waste provided high capital costs for small quantities of GHG mitigation (increasing GHG emissions from fish hydrolysate and dried fish).

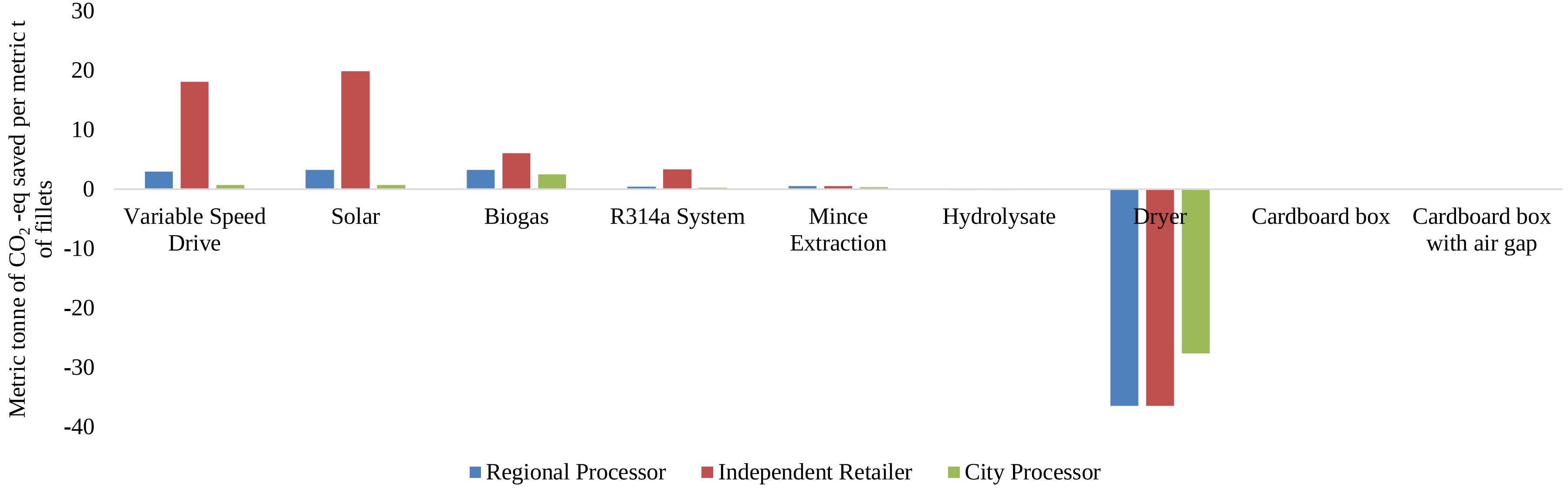

Figure 5.12 Potential GHG reduction from each CPS

Table 5.46 GHG mitigated per $ of investment (kg of CO_2 –eq) from each CPS for the Regional Processor

Variable speed drive	Solar	Biogas	R134 System	Mince extraction	Hydrolysate	Dryer	Cardboard box	Cardboard box with air gap
0.017	9.97[a]	6.25	1.697	0.015	-0.033	-6.025	N/A[b]	N/A[b]

[a] Includes solar rebate for comparison. Quote for City Processor did not separate capital costs and solar rebate
[b] No capital equipment is required

Table 5.47 GHG mitigated per $ of investment (kg of CO_2 –eq) from each CPS for the Independent Retailer

Variable speed drive	Solar	Biogas	R134 System	Mince extraction	Hydrolysate	Dryer
0.187	1.47[a]	1.09	N/A[b]	0.010	-0.022	-4.100

Table 5.48 GHG mitigated per $ of investment (kg of CO_2 –eq) from each CPS for the City Processor

Variable speed drive	Solar	Biogas	R134 System	Mince extraction	Hydrolysate	Dryer
0.004	2.51	2.28	0.085	0.021	-0.046	-8.549

Cost benefit analysis

A summary of the difference in CPS NPV from each current system from each sector is presented in Tables 5.49-5.51.

Recycling waste into hydrolysate had the highest potential long term profit in the regional processor and city processor ($ 764,364.34 and $ 1,461,165.40 over 15 years respectively). Replacing the refrigeration equipment provided the highest potential long term profit for the independent retailer as it reduced their current lease cost with no capital costs ($ 1,070,375.18). As solar electricity provided the best GHG reduction, it also provided a potential long term profit in the regional processor and city processor by reducing electricity costs ($ 143,035.87, $ 624,324.55 and $ 65,887.63 respectively).

Table 5.49 Difference in CPS NPV from the current system for the Regional Processor

Variable speed drive	Solar	Biogas	R134 System	Mince extraction	Hydrolysate	Dryer	Cardboard box	Cardboard box with air gap
-$ 24 656.52	$ 143 035.87	$ 195 563.73	$ 86 166.33	-$ 232 035.40	$ 764 364.34	-$ 2 203 263.59	$ 1 450.13	-$ 11 076.36

Table 5.50 Difference in CPS NPV from the current system for the Independent Retailer

Variable speed drive	Solar	Biogas	R134 System	Mince extraction	Hydrolysate	Dryer
$ 404 443.91	$ 624 324.55	-$ 10 670.33	$ 1 070 375.18	-$ 213 301.14	$ 234 844.21	-$ 1 773 180.04

Table 5.51 Difference in CPS NPV from the current system for the City Processor

Variable speed drive	Solar	Biogas	R134 System	Mince extraction	Hydrolysate	Dryer
-$ 22 826.80	$ 65 887.63	$ 39 982.12	$ 35 395.50	-$ 230 083.82	$ 1 461 165.40	-$ 2 858 326.28

5.6.3. Quality assessment

The electricity and recycling CPSs did not affect the original final fish fillet. The fish mince required handling according to HACCP instead of waste product. The fillet packaging indicated cardboard boxes do hold the temperature, drip loss, quality index, microbiology and texture of fish fillets.

5.6.4. Summary

In summary, recycling fish waste into hydrolysate provided the highest potential profit for all sectors measured. When combining the PLCA, economic and quality results, solar electricity provided the highest GHG reduction and the highest potential profit for the regional processor and the independent retailer and biogas for the city processor. This conclusion comes as solar has the highest potential GHG reduction and the highest GHG reduction per $ 1 of investment in the regional processor and the independent retailer, does not impact on quality, and provided a potential long term profit from the NPV. Similarly, biogas provided the highest potential GHG reduction, the highest GHG reduction per $ 1 of investment, the second highest NPV, and no quality issues when comparing the options investigated for the city processor.

5.7. Discussion

This research has identified potential CPSs and assessed them using PLCA, economic analyses and quality analysis. The potential CPSs covered the GHG hotspots identified in Chapter 4: electricity, refrigeration gases, filleting waste and fillet packaging. As the use of these CPSs are discussed below, it is necessary to note that this is a new area in seafood research, combining PLCA, economic opportunities and product quality. As a result, the application of electricity CPS (including variable speed drives and solar electricity) and refrigeration gas alternatives are discussed from the general literature. CPSs including biogas, recycling waste and fillet packaging are discussed from current seafood literature.

5.7.1. Electricity alternatives

In the current study, electricity had the highest GHG emissions in all sectors measured. Therefore, the implications of variable speed drive installation on all refrigeration and freezer units (a good housekeeping CPS), and electricity substitution using solar electricity and biogas (input substitution CPSs) were assessed.

Electricity as a hotspot is primarily related to refrigeration and the temperatures required to keep fish food-safe. Other LCA studies in the food industry have also identified electricity as a hotspot including fish (Hobday et al., 2014; Vázquez-Rowe et al., 2011a; Vázquez-Rowe et al., 2010b; Vázquez-Rowe et al., 2013; Winther et al., 2009), frozen spinach (Sanjuan et al., 2014) and ice cream (Australian Industry Group, 2011). However, previous seafood studies identified diesel from the harvest stage as the greatest hotspot (Hobday et al., 2014; Vázquez-Rowe et al., 2011a; Vázquez-Rowe et al., 2010b; Vázquez-Rowe et al., 2013; Winther et al., 2009), in contrast to the electricity consumption from processing and retail identified in this study. As a result, there is the opportunity to reduce the electricity consumption or substitute the electricity source.

The installation of variable speed drives has the potential to reduce 10.8 %, 19.4 % and 17.8 % of GHG emissions in the regional processor, independent retailer and city processor respectively. This CPS was more effective in the regional processor and independent retailer as they had a higher electricity consumption per metric tonne of fillets than the city processor. Previous research on general variable speed drive installation indicated a similar scenario by a greater than 50 % reduction when comparing refrigeration equipment generally (Shim et al., 2014) and a 30 % reduction in ice cream production (González-Ramírez et al., 2013).

Solar electricity had both the highest GHG reduction in the regional processor and independent retailer, and the highest GHG reduction per $ 1 of capital investment in all three facilities. The Australian government provides assistance to industries wanting to utilise solar electricity through Small-scale Technology Certificates (STCs) (Clean Energy Council, 2014) by subsidising capital costs. As many businesses do not own their premises, there is also an option of leasing solar equipment from the landlord (Clean Energy Council, 2014; Council of Australian Governments (COAG) National Strategy on Energy Efficiency, 2012). These agreements work by paying the landlord or a licenced solar installer the costs saved from the solar installation, improving the feasibility of solar installation within industry.

Whilst solar is useful to supplement grid electricity during the day, grid electricity is still required. Gilmore et al. (2015) discussed the current costs of storing solar electricity in Queensland and New South Wales, concluding that it is currently more expensive per kWh than grid electricity, but with increased demand and improved solar storage equipment, it is likely to become more economical. Furthermore, storing solar electricity in a battery format requires a charge and discharge, utilising a portion of the solar electricity harvested (Gilmore et al., 2015). Therefore, solar electricity is only recommended in the selected supply chains as a supplement to the current grid electricity until further research and demand provides a more economic and efficient method of storing solar electricity.

Biogas facilities are usually located in areas where fish processing plants have the opportunity to combine fish waste with other industrial waste such as oil (Wang et al., 2015). Ronde et al. (2010) demonstrated the use of oil extracted from fish waste converted to enough biogas to fuel the refrigeration equipment for the processing facility. However, although research from Ronde et al. (2010) applied fish biogas in a commercial setting, most seafood biogas studies have only been on a laboratory scale size (Arvanitoyannis and Kassaveti, 2008; Chen et al., 2010; Curry and Pillay, 2012; Gebauer, 2004; Gumisiriza et al., 2009; Kafle et al., 2013; Nges et al., 2012). These studies all differed in gas output due to the protein content of the original product. Huttunen et al. (2014) described these differences depend on the raw material, use of gas, digestion process, and use of digestate.

When applying biogas to a facility, several factors need to be considered. The biogas processing plant needs to be onsite for two reasons; for ease of disposing of filleting waste and so the energy is connected directly to the processing or retail facility. However, potential odours from the waste need to be either well sealed, or away from the facility, particularly from customers if the facility is in a retail setting. The filleting waste also needs to be separated from other waste such as plastic (Davidsson et al., 2007). Therefore, both the location of the facility and the handling of the waste need careful planning before implementation.

Economically, solar electricity is the best option of the CPSs investigated for the regional processor and independent retailer, reducing 4.37 kg and 1.49 kg of GHG per $ 1 of investment respectively. Solar also provided a positive NPV difference of $ 142,978.31 and $ 414,675.88 in the regional processor and independent retailer respectively, indicating potential profit from the investment. Although biogas indicated a potential higher profit than solar electricity in the regional processor, it requires a larger initial investment and ongoing maintenance, whereas solar electricity has an initial low capital cost and no maintenance or ongoing operations. Variable speed drives my also potentially provide profit for the independent retailer, but less than solar. The regional processor would not recover costs from variable speed drives in a 15 year period.

As the city processor had an initial low electricity consumption per metric tonne of fish compared to the regional processor and independent retailer, the economic opportunities differed. This difference also occurred because the city processor had a larger quantity of fish waste in the facility for biogas production that would recover capital costs. Therefore, biogas indicated the largest GHG reduction per $ 1 of investment of the CPSs compared (2.31 kg of GHG per $ 1 of investment). However, as discussed above, biogas production requires regular maintenance and may produce an odour, so until specialised equipment (instead of a “homemade” version) and the capacity to outsource the maintenance is regularly available, solar electricity (which had 1.04 kg of GHG per $ 1 of investment and a NPV difference of $ 65,887.63) may be an easier option. Costs would not be recovered from variable speed drives in the city processor in the 15 year period as electricity consumption is already efficient.

Electricity consumption can be reduced by variable speed drives or substituted with solar or biogas electricity. All potentially reduced the GHG emissions, with solar the most effective in the regional processor and independent retailer and biogas the most effective in the city processor.

5.7.2. Modifying refrigeration equipment

As refrigeration gases had the second largest GHG emissions in all the supply chains, equipment with alternative refrigerants were investigated. The R134a refrigerant only had 40 % of the GHG emissions when compared to the current R404a equipment (Department of Sustainability Environment Water Population and Communities, 2012), and was more electricity efficient (He et al., 2014) thus potentially reducing the GHG emissions in the sectors measured. Furthermore, as the independent retailer and city processor lease their equipment, the R134a equipment is cheaper to lease than the current systems in place, resulting in long term savings with no capital costs. As the regional processor's equipment is fixed into the premises, a large capital cost is required to replace and install a new system capable of using R134a.

Others have investigated the impact of different refrigerant gases including ammonia (R717) and carbon dioxide (R744). Whilst these have a low GHG emission (0 and 1 kg of CO_2 –eq per kg of ammonia and carbon dioxide refrigerants refrigerant respectively) (Restrepo et al., 2008), pre-made systems (such as the sectors in this study use) are not currently available in Australia to buy or lease. Instead, each facility is required to design ammonia or carbon dioxide systems specific to their business with the refrigeration company before potential capital and running costs are available, making cost benefit analyses difficult to calculate without prior purchasing commitment. R717 systems tend to have a high capital cost, but lower ongoing costs than systems such as the current R404a.

Economically, changing the refrigeration system to R134a provided a potential profit for all sectors measured, despite the large capital cost for the regional and city processor (as they did not lease). R134a was a cheaper gas to purchase and equipment was more electricity efficient. The independent retailer had a larger potential profit as they lease their refrigeration equipment resulting in both a lower lease cost and no capital investment required. Consequently, changing the refrigeration system to R134a provided a potential profit and GHG reduction in all sectors.

5.7.3. Recycling filleting waste

When considering the fish waste in landfill, of the options explored in this study, only mincing potentially reduced GHG emissions in all sectors considered: both hydrolysate and drying increased the current GHG emissions. However, as mincing, hydrolysate and drying create a new product from waste, the economic implications are more important to industry. Therefore, as the hydrolysate process has a potential long term profit as a fertiliser product (confirmed by Knuckey et al. (2004)), it is currently more appealing to industry.

This study used formic acid to make hydrolysate which was then sold as fertiliser. The hydrolysate product is also possible using alternative chemicals such as phosphoric acid (Fetter et al., 2013), or enzymes such as alcalase (Bhaskar et al.,

2008) and protease (Bhaskar and Mahendrakar, 2008). The enzyme methods were unsuccessful in breaking down fish bone (Western Kingfish Limited, 2008) which is insignificant in fertiliser products, but can cause a problem if the hydrolysate is used for human consumption. Fish fertiliser has also been made by autoclaving and composting (Dao and Kim, 2011), composting (López-Mosquera et al., 2011) and inoculating the waste with earthworm bacteria (Kim, 2011).

Whilst hydrolysate has been confirmed to be successful as a fertiliser (Fetter et al., 2013), others have used hydrolysate for other purposes. For example, fish waste hydrolysate has been used for fish feed (Hernández et al., 2013; Murray et al., 2003; Refstie et al., 2004; Western Kingfish Limited, 2008), and pharmaceuticals for the antioxidants (Samaranayaka and Li-Chan, 2008) with potential to reduce cholesterol in rats (Wergedahl et al., 2009). Thus, after the process is applied in Western Australia there is potential for further research into creating products for alternate uses including human consumption.

Fish mince was the only waste CPS with a potential GHG reduction. Whilst initial capital costs may slow application in the Western Australian seafood industry, fish mince is cheap to produce and can be sold for human consumption. However, as the product is designed for human consumption, the waste needs to remain under refrigerated conditions and the mince either used or frozen immediately to maintain quality as in optimum condition, fish mince has a shelf life of nine days in aerobic conditions or 17 days under MAP conditions (Chatli et al., 2012). Such mince has been used overseas to make extruded snack products (Lakshmi Devi et al., 2013), fish cakes and fish fingers (Keay, 2001), surimi (Cortez-Vega et al., 2013) and cutlets (Shrangdher et al., 2013). Therefore, there is further opportunity to develop this waste product into a more profitable product.

The dryer had a large GHG emission and was expensive to run as it was a pilot scale machine. However, future work may provide a more efficient system as dried seafood products are used overseas for aquafeed (Gunasekera et al., 2002) and dried sea cucumber is produced in China (Qian et al., 2012). Howieson et al. (2013) also recommended the dried product could be used in high protein supplements, dashi fish stock powder, premium pet food and fish oil. As opposed to freeze and oven drying, vacuum drying allows product rehydration (Qian et al., 2012), reduced shrinkage

(Qian et al., 2012; Tsuruta and Hayashi, 2007) and a controlled moisture content with a short drying time (Tsuruta and Hayashi, 2007). Consequently, dried seafood waste products have potential in Australia, but firstly require efficient and economical equipment.

Economically, hydrolysate is the best option of the CPSs investigated for the regional processor, independent retailer and city processor, producing a NPV difference of $ 1,329,615.45, $ 800,095.32 and $ 2,026,416.51 respectively. The costs of mincing and drying would not be covered unless the mince is further value-added and the drying machine increased in capacity to reduce electricity consumption. Whilst the hydrolysate does increase GHG emissions, it does reduce waste and potentially provide a profit. However, the hydrolysate partnering firm of this study cannot always sell their product, providing scope for further marketing and research in in this area.

Whilst only mincing, hydrolysate and drying were covered in this project, these were only a snapshot of potential filleting waste options. Processed seafood by-products are currently used overseas for fish feed (Gunasekera et al., 2002), bait (Svanes et al., 2011b), pet food (Thrane et al., 2009a), and a source of lactic acid for plastic production (Gao et al., 2006). Edible products including fish sauce (Shih et al., 2003), fish oil (Garcia-Sanda et al., 2003; Thrane et al., 2009a; Wu and Bechtel, 2008) and calcium (Iribarren et al., 2010b) can also be produced from processing fish waste. As creating products from waste is a recycling cleaner production strategy applied throughout the world, it needs to be profitable in the long term as described by Archer et al. (2005).

5.7.4. Fillet packaging

Polystyrene eskies used in the storage and transport of fish fillets pose a problem for the seafood industry due to their inability to store flat, difficulty to reuse (due to their hard to clean nature) and difficulty to recycle, particularly in regional Western Australia. CPSs for the regional processor on strategies to reduce their polystyrene consumption were therefore also investigated in this research.

Results indicated substituting cardboard boxes for polystyrene reduced the GHG emissions in the regional processor. Although cardboard does not provide the insulation of polystyrene, quality results indicated it held the temperature equivalent to polystyrene under refrigerated conditions. As the Food Standards Code requires seafood products to be stored below 5 °C or above 60 °C (FSANZ, 2014b), if seafood products are not in refrigerated conditions at all time, the supply chain requires modification. Navaranjan et al. (2013) recommended cardboard boxes as a suitable for fish transport in New Zealand as no significant temperature or quality differences in whole fish stored in polystyrene and insulated cardboard boxes were determined. Furthermore, many meat products use cardboard boxes as outer packaging (Heinz and Hautzinger, 2010) even though stringent temperature control is still required to maintain the remaining shelf life and product quality (Olley and Ratkowsky, 1973). Similar temperature studies have also occurred using corrugated plastic, resulting in another potential alternative to polystyrene (Margeirsson et al., 2009; Margeirsson et al., 2011; Margeirsson et al., 2012). Again, Margeirsson et al. (2012) recommended these corrugated plastic containers for temperature controlled supply chains.

If polystyrene substitution is not an option for the seafood industry, it can also be recycled. Polystyrene has been recycled into fuel (Abnisa et al., 2013), styrene recovery (Ke et al., 2005; Ukei et al., 2000) and oil filters (Shin, 2006). Polystyrene recycling is currently used in Australia at Sydney Fish Markets, processing 109.3 metric tonne of polystyrene since December 2012 (Sydney Fish Market, 2014). Whilst polystyrene recycling has not been covered in this project, the potential GHG reduction and economic prospects leave scope for further research.

5.7.5. Combination of cleaner production strategies

Although CPSs, their potential GHG reduction, economic and quality impacts have been investigated, combining several CPSs together may prove more effective. For example, whilst the mincing CPS reduced landfill, fish heads, frames and guts still remained and could potentially be used for biogas, hydrolysate or dying. Furthermore, as the introductions of some CPSs discussed have a potential long term profit (e.g. solar panels in all supply chains), the cost savings may be used to subsidise CPSs with a high capital cost (e.g. variable speed drives).

5.7.6. Supply chain comparison

In summary, the three supply chains used in this research indicate there is no single solution to reduce the GHG emissions from the Western Australian finfish supply chains. As different facilities have different processes, fish quantities, locations, equipment and electricity consumption, each facility requires a separate analysis to determine the most effective and economical CPS.

The size of the facility influenced the effectiveness of varying CPSs. As the city processor had the largest quantity of fish (and thus, filleting waste) per year, a biogas facility could potentially produce enough electricity to be profitable. However, the regional processor and independent retailer's waste was not in sufficient volumes to recover biogas capital and maintenance costs from grid electricity savings, indicating the quantity of fish and waste influenced the economic opportunities for each facility.

The location of each facility influenced the cost and ownership of refrigeration equipment and thus, potential CPS implementation. As the regional processor was located 1,000 km away from the nearest capital city, the refrigeration equipment was owned rather than leased. The cost of leasing the equipment included all maintenance and provided the facility with the option of upgrading the equipment every two years. Therefore, the independent retailer and city processor have the option of leasing refrigerators which use the R134a refrigerant once their lease period ends (or they choose to replace their equipment), whereas the regional processor will have to purchase the equipment outright, pay for transport to the site and installation costs if they wished to replace the current refrigerant, resulting in a large upfront cost. In contrast, by owning the equipment, installing upgrades such as variable speed drives is feasible, whereas leased equipment maintenance is determined and performed by the leasing agency. Consequently, CPSs requiring refrigeration equipment upgrades or modifications depend on whether the facility owns or leases their refrigeration equipment.

The current electricity consumption also influenced which CPS had a greater GHG reduction. As the regional processor and independent retailer had a larger electricity GHG emission per metric tonne of fish fillets than the city processor (Chapter 4, Tables 4.7-4.9), the effectiveness of all electricity reduction CPSs differed. As the city processor had a small GHG emission from electricity (1,777.041 kg CO_2 –eq per metric tonne of fillets, Chapter 4:Table 4.9), compared to the regional processor and the independent retailer (7,440.579 and 84,068.195 kg CO_2 – eq per metric tonne of fillets respectively, Chapter 4: Tables 4.7 and 4.8). Therefore, as the regional processor and independent retailer had a larger electricity consumption, variable speed drives indicated a larger potential GHG reduction than in the city processor. Consequently, the current electricity consumption influenced the CPSs with the greatest potential GHG reduction.

5.8. Conclusion

The potential greenhouse gas emissions and economic implications differed between supply chains due to the quantity of fish each supply chain received and consequently, the quantity of filleting waste, the initial electricity consumption, the location of each facility and whether facilities owned or leased their refrigeration equipment.

When combining the PLCA, economic and quality results, solar electricity was the simplest CPS to implement in all sectors, providing GHG reduction and the potential profit. Whilst recycling fish waste into hydrolysate provided the highest potential profit for all sectors measured (but not GHG reduction), further work is required to seek and maintain a market. Biogas production also provided a potential profit and GHG reduction, but until biogas becomes more prominent in Australia and specific systems are designed, they will require high maintenance and possibly release an unpleasant odour.

Chapter 6 will further explore the implications of CPS implementation in the Western Australian finfish supply chain and areas requiring additional research.

5.9. Paper 2: Greenhouse gas emissions from a Western Australian finfish supply chain

Paper two is an accepted peer reviewed journal article that addresses objectives one and two of the thesis from two of the supply chains measured in Chapter 4 and initial results from Chapter 5.

The thesis objectives covered in this paper were:

1. Identify the areas of greatest greenhouse gas emissions from selected Western Australian seafood supply chains
2. Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs

Greenhouse gas emissions from a Western Australian finfish supply chain

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Keywords: Greenhouse gas Finfish supply chain Life cycle assessment

Abstract

Greenhouse gas (GHG) emissions in the form of carbon dioxide equivalent (CO^2 eq) from two Western Australian finfish supply chains, from harvest to retail outlet, were measured using streamlined life cycle assessment methodology. The identification of interventions to potentially reduce the GHG emissions was determined from the results obtained. Electricity consumption contributed to the highest GHG emissions within the supply chains measured, followed by refrigeration gas leakage and disposal of unused fish portions. Potential cleaner production strategies (CPS) to reduce these impacts included installing solar panels, recycling the waste, good housekeeping in refrigeration equipment maintenance, and input substitution of refrigeration gas. The results show a combination of these strategies have the potential to reduce up to 35% of the total GHG emissions from fillet harvest, processing and retail.

1. Introduction

The atmospheric concentration of greenhouse gases (GHG), including carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O), is increasing (Forster et al., 2007). Airborne particles in the gases then absorb more heat, thus resulting in global warming which causes climate change (Forster et al., 2007). To minimise potential increases in temperature, primary industries that release GHG (such as the seafood industry) should apply cleaner production strategies (CPS) to combat climate change (UNEP, 2002). This paper focusses on the global warming impact of the resources utilised in two Western Australian seafood supply chains by calculating the GHG per tonne (t) of fish fillets.

Streamlined life cycle assessment (SLCA), following the steps of International Organisation for Standardization (2006) is the most widely used method for measuring the upstream GHG emissions only, not taking into account the complete product life cycle (Biswas et al., 2010; Engelbrecht et al., 2013; Gunady et al., 2012). Its application models the GHG emissions for the current study.

Numerous studies have concentrated on modelling GHG emissions and other environmental impacts from harvesting fish (Table 1). However, none of these studies includes data from Western Australia where water temperature, fish species, vessel types and logistics, particularly the long distances from port to fishing ground, differ from other countries.

Several SLCA studies have also investigated the environmental impacts of different transport methods of fish once landed to determine the most environmentally friendly and economic system. Studies included the impact of transporting methods for fresh (never been frozen) and frozen fish (Andersen, 2002; Va'zquez-Rowe et al., 2012) and comparing truck (Andersen, 2002; Kissinger, 2012; Tlusty and Lagueux, 2009; Va'zquez-Rowe et al., 2012), air (Andersen, 2002; Tlusty and Lagueux, 2009; Va'zquez-Rowe et al., 2012), boat (Andersen, 2002; Kissinger, 2012; Vazquez-Rowe et al., 2012), and rail (Kissinger, 2012) transportation methods. However, Western Australia's case differs from these studies as in some cases fish is transported over 2000 km from the port to the nearest capital city (Department of Fisheries, 2012).

This study is also unique in combining the three supply chain stages in finfish production: harvesting, processing and retailing. The process in environmental supply chain management requires all stakeholders in a supply chain to work together to measure the impact and identify strategies to attain economically viable out- comes with low GHG emissions (Gupta and Palsule-Desai, 2011). Sustainable seafood supply chain management is working as a whole supply chain with the intention of reducing life cycle environmental impact, enhancing social equity and reducing operational costs therefore, increasing profit. In seafood supply chains, previous environmental research studies have only focussed on the harvest (Iribarren et al., 2011; Svanes et al., 2011b; V'azquez-Rowe et al., 2011b; Ziegler et al., 2011), processing (Bezama et al., 2012; Hospido et al., 2006; Williams and Wikstro€m, 2011) and transport stages (Coley et al., 2011; Tlusty and Lagueux, 2009) in the supply chain; only Winther et al. (2009) and Ellingsen et al. (2009) followed harvest through to value adding, but ignored the retail stage. Thus a combination of the whole Western Australian seafood supply chain GHG emissions provides a more effective picture of environmental supply chain management as described by Denham et al. (in press).

Food LCA studies specific to Australia follow a similar trend with only 6% covering the retail stage within the supply chain (Renouf and Fujita-Dimas, 2013). Only Hobday et al. (2014) covered the whole seafood supply chain in Australia, but did not cover the species and transport distances associated with Western Australian finfish.

To fill these gaps of the Western Australian finfish industry knowledge and add to the whole supply chain research, this study has aimed to analyse the Western Australian finfish supply chain's GHG from harvest to retailer. The specific objectives were to:

a) assess the global warming impact of the harvest, processing and retail stages of two Western Australian finfish supply chains using a SLCA method;

b) identify the ‘hotspots’ or the inputs and outputs emitting the highest amount of GHG during the life cycle of the finfish product; and

c) recommend opportunities for possible GHG CPS.

1.1. Description of finfish supply chains examined

The fish was trawl harvested in the North Coast Bioregion as described by The Department of Fisheries (2012). The boat travelled approximately 200 km from port before trawling started. The post- trawl fish process included emptying the catch into a hopper, sorting by size into baskets (or polypropylene bags for large fish), cooling in seawater brine for four hours and packing into tubs for cool room storage once the fish reached 0° C. Once the boat arrived at port after ten days at sea, the fish were packed onto pallets by species and unloaded off the boat, onto a truck. The boat under- went cleaning and maintenance before it returned to sea.

City retailers handle a larger quantity than the regional retailers so, from the landing of the harvested fish, two supply chains were chosen for this SLCA analysis, one to a city retailer and one to a regional retailer. The city retailer was located more than 1,000 km away from the landing port whereas the regional retailer was within 20 km.

- The city retailer processed the fish into fillets on site as required, instead of using a dedicated filleting processing facility.
- The regional processor filleted, packaged and transported fillets to local and surrounding restaurants and the regional retail outlet.

Hence, in summary there were two separate supply chains from landing: chain one with three firms e harvesting, regional pro- cessing and regional retailing; and chain two with two firms e harvesting and city retailing. The system boundaries of this research (Fig. 1) included transportation of all consumable items to their respective stages and fish waste disposal to landfill. The sys- tem boundaries of the proposed SLCA excluded all downstream activities, including food service and restaurant sectors and handling after the product left the retail facility.

As seafood handled in the processing and retail facilities included other seafood products (e.g. crustaceans), an allocation procedure separated inputs for the finfish products by weight. The inputs allocated included power, water and refrigeration gases as data provided was per facility.

The selected trawl firm provides 20.5% of the finfish from the North Coast Bioregion (Department of Fisheries 2012) where 73% of the finfish in this region was trawl caught. The species in this region differ from other regions in Western Australia, as the large coastline results in various water temperatures throughout Western Australia. Therefore, this study is representative of firms dealing with species such as Crimson snapper (*Lutjanus erythropterus*), Bluespotted emperor (*Lethrinus punctulatus)* and Rosy threadfin bream (*Nemipterus furcosus*).

From this capture, 8.7% of the fish caught are utilised in the regional processor and 5.9% in the city retailer. The remaining fish is sold to a private processor. Although these supply chains are only a sample of Western Australia's seafood industry, the framework can still be applied in other companies. The study covers the supply chain from capturing the fish, to leaving the retail store, including typical trawling, processing and retailing processes with similar inputs and outputs. The only items that may differ from other Western Australian fresh finfish supply chains are the transport distances of both consumable items to site and fish to processor or retailer, and the method of packaging (whether fillets are packed loosely in carton liners as per the regional processor or if they are vacuum packed). These variations are beyond the scope of this research.

2. Standard methods for streamlined life cycle assessment

The GHG emissions from the Western Australian test seafood supply chain was benchmarked using a streamlined approach, as it did not take into account downstream activities such as fish consumption. This SLCA approach undertaken followed the four steps of International Organisation for Standardization (2006): goal, life cycle inventory, impact assessment and interpretation. The goal was to ascertain the GHG emissions from the Western Australian finfish supply chain. The functional unit was one tonne of processed fish sold at retail. This unit was used to determine the number of stages of fish life cycle for developing an inventory. The inputs (i.e. chemicals, energy) and outputs (i.e. emissions from processes) were quantified for each life cycle stage for developing inventories of one tonne of processed fish sold at retail for city and retailer supply chains. Some of the data for developing inventories came from field survey, while the rest of the data was obtained from literature.

Collaborating firm interviews occurred between August 2012 and September 2013 and were compiled in a life cycle inventory (LCI) spreadsheet. The LCI considers all the relevant inputs and outputs for processes that occur during the life cycle of a product. Inventory data was categorised into consumable items, energy, transport, storage and waste (Table 2).

Preliminary data for LCI: Representatives from each of the supply chain stages, including a trawler off the coast of regional Western Australia, a regional processor, a regional retailer and a city retailer were interviewed face to face to obtain primary information using a structured questionnaire.

The harvest data includes the quantity of fish harvested, diesel and boat maintenance required per year.

The processing and retail data included the quantity of fish purchased, fish waste and its final destination to landfill, electricity and water consumption, consumable materials and the distances all travelled to the site.

Secondary data for LCI: Secondary data included different data sources:

- international literature provided data estimation from elements that were not possible to collect from the field (i.e. refrigeration gas leakage);
- medical safety data sheets for chemical quantities;
- national reports for waste emission recovery and bioelectricity production; and
- international databases to calculate the eco-inventories of raw materials and energy sources (i.e. packaging materials, gloves, chemicals, boat maintenance and paper).

Once the inventory has been developed using both primary and secondary data sources, emission factors for all inputs and outputs were developed for assessing the life cycle GHG emissions of one tonne of fish fillets sold at retail.

Each CO_2, CH_4 and N_2O gas emission from the LCI was developed. The inputs and outputs of the LCI were multiplied by the respective emission factors (Table 3). Energy emission factors were applied to consumable materials when only an energy breakdown analysis was available. Once the inputs were estimated for the production of one tonne of fish fillets sold at retail, then these inputs were multiplied by their respective emission factors. These emission factors were mainly sources from the local databases. In the absence of the local database, new emission data base were created for the inputs (e.g. battery emissions (Lankey and McMichael, 2000; Life Cycle Strategies Pty Ltd, 2012)).

Energy emission factors: Energy included electricity, diesel, steam, LPG, natural gas, crude oil, coal and petroleum and was calculated from Life Cycle Strategies Pty Ltd (2012). These emission factors were also used for consumable materials when only an energy breakdown analysis was available. The energy breakdown for batteries was taken from Lankey and McMichael (2000).

Storage emission factors: Storage included ice production and refrigeration. All refrigeration gas emission factors were calculated using the leakage rates from The Australian Institute of Refrigeration (2012) (30% for boats, 12.5% for walk in cool rooms and 12.5% for display cabinets) and the emission factor from The Department of Sustainability, Environment, Water, Population and Communities (2012) (Table

3). The ice machine energy breakdown and the water and refrigerant quantities contributed to the ice emission factor.

Transportation emission factors: Transportation included of transportation of consumables and fish each facility and was calculated from Life Cycle Strategies Pty Ltd (2012) for ship, inter- national airfreight, articulated truck, car, light commercial vehicles and rail transportation. The refrigerated truck had 20% more energy (Tassou and Ge, 2008).

Waste emission factor: The waste emissions from unused fish portions in this research including heads, viscera, scales, bones, tails etc. were calculated to be 1.39 kg of CO_2 e eq per kg of fish using the Buswell equation (Symons and Buswell, 1933), composition of the waste (Esteban et al., 2007; Khoddami, 2012; Ng, 2010) and anaerobic digestion yields (Curry and Pillay, 2012; Davidsson et al., 2007) to calculate the methane emitted to the atmosphere, instead of harvested for energy. Although some landfill sites in Western Australia are harvested for methane, the average of 38.9% of CH4 recovered from landfill (Department of the Environment) and the resulting 45.289 kWh of energy per functional unit (Clean Energy Council, 2013) was included in the waste emission factor.

Finally, following IPCC's fourth assessment report (Forster et al., 2007), all GHGs associated with the production of one tonne of fish fillets sold at retail were converted to 100 year impacts in kg of CO_2 eq.

After the SLCA, CPS were assessed to mitigate supply chain GHG emissions. These five categories of strategies are described further in UNEP (2002) and van Berkel (2007):

1. Good housekeeping
2. Input substitution: replacing resources with environmentally preferred substances
3. Technological modification: modifying existing structures to increase efficiency
4. Product modification: modifying a product to reduce material consumption and to enhance recyclability

5. Recycling waste.

3. Results and discussion

3.1. Comparison of the city and regional supply chains

Although both supply chains include transporting the fish from the port, filleting and storage, the supply chain's inventories differed (Table 4). The regional supply chain had an extra stage and the city supply chain consumed more electricity due to a larger and potentially more inefficient refrigeration system; the city supply chain consumed more than six times the electricity consumed in the regional supply chain. The city supply chain also had more tkm (tonnes x km travelled) of refrigerated transport to get the fillets to the retailer due to the large distance from port.

Producing one tonne of fish fillets released a total of 18,870 kg CO2 e eq from the regional supply chain and 92,560 kg CO2 e eq from the city supply chain (Fig. 2). The Monte Carlo Simulation was run to determine the mean, standard deviation and standard error of the mean from each supply chain (Table 5). The standard deviations were only 2.8% and 3.9% of the mean values of the carbon footprint of the regional and city supply chains, respectively, con- firming the validity of this LCA.

3.2. Identification of hotspots

Relative impacts from the various supply chain components are shown in Fig. 3. The greatest GHG emissions within the two supply chains measured were from energy, mainly electricity consumption (76% in the regional supply chain and 94% in the city supply chain) followed by refrigeration gases (11% in the regional supply chain and 4% in the city supply chain) and filleting waste (6% in the regional supply chain and 1% in the city supply chain).

Energy consumption was also the hotspot in other seafood LCA studies, however, in this study, the energy use was from electricity used in processing and retail, rather than diesel consumption in the harvest stage as found by Winther et al. (2009), Thrane (2004), and Va'zquez-Rowe et al. (2010b, 2011b).

Whilst the supply chains measured required long distant transport (>1,000 km), the transportation had a minimal impact in the regional (1.7%) and city (0.04%) supply chains. This is because each consumable purchased had a relatively low weight, resulting in a low tkm. Transport of fish to the city retail outlet had a larger impact than transporting the consumable items to the boat, regional processor and regional retailer.

When comparing these results to previously published work, few studies had the same areas of greatest impact perhaps because they did not include the whole supply chain (Ellingsen et al., 2009; Svanes et al., 2011b; Va'zquez-Rowe et al., 2013; Winther et al., 2009; Ziegler et al., 2013), excluded refrigeration gases (Iribarren et al., 2010; Thrane, 2006; Va'zquez-Rowe et al., 2011b) or the supply chains did not use refrigerants with a high GHG emission factor (Winther et al., 2009). Previous seafood LCA studies either focussed on the harvest supply chain stage, where energy use was diesel (Ellingsen and Aanondsen, 2006; Svanes et al., 2011a; Winther et al., 2009) or focussed on the processing and retail stages that require electricity used in processing (Va'zquez-Rowe et al., 2013; Winther et al., 2009).

If this study excluded the refrigerant leakage, the emissions would be underestimated by 11% and 4% from the regional and city supply chains respectively. Va'zquez-Rowe et al. (2013), Ziegler et al. (2013) and Svanes et al. (2011b) found refrigerant leakage to be a hotspot during harvest but did not measure beyond harvest into processing and further handling. Although Iribarren et al. (2010) originally did not include refrigerants in his research, in a later study he found refrigerant leakage to have the greatest carbon emissions from fish capture (Iribarren et al., 2011). Other studies including Thrane (2006) and V'azquez-Rowe et al. (2011b) ignored refrigeration completely in their research. Winther et al. (2009) did include refrigerants, but the study comprised of carbon neutral alternatives. As a result, the energy used in the harvest was the hotspot (Thrane, 2006; V'azquez-Rowe et al., 2011b; Winther et al., 2009; Ziegler et al., 2013) with minimal GHG from processing and retail. None of these aforementioned studies included fish waste.

3.3. Potential cleaner production strategies

As the three greatest GHG hotspots within both supply chains were energy from electricity, refrigeration gas leakage from the cool rooms, ice machines, and display cabinets, and the breakdown of fish waste in landfill, potential CPS are discussed. These include installing solar panels (an input substitution CPS as it is associated with the replacement of conventional electricity solar electricity), the conversion of fish waste to bio-electricity (input substitution, technological modification and recycling CPS) and reducing the GHG emissions from refrigerant leakage equipment (a good housekeeping CPS).

3.3.1. Solar electricity

Electricity as a hotspot is related to refrigeration as low temperatures are required to keep fish food-safe. Other LCA studies in the food industry have found a similar energy hotspot including Sanjuan et al. (2014), V'azquez-Rowe et al. (2013) and Winther et al. (2009). As most of the energy consumption from the supply chains measured in this study is electricity, there is the opportunity of harvesting solar energy as a potential CPS.

Solar energy (an input substitution CPS) is useful for supplementing the bulk of the power used during the day. As the energy consumption from the partnering firms was from refrigeration and freezing non-fish products, it is assumed energy consumption is consistent over a 24 h period. Therefore, solar panels can be used to supplement grid electricity during the peak sun hours of the day. Peak sun hours are the time per day the sun provides the maximum solar energy, differing in various locations around Australia and in different seasons of the year. The average peak sun hours were calculated from BOM (2013) for both the regional processer and city retailer regions. The solar emission factor was taken from Lund and Biswas (2008) (multicrystalline solar system at 0.075 kg of CO2 e eq per kWh). Due to the total energy consumption, a 20 kW and a 100 kW system is recommended for the regional processor and the city retailer respectively, resulting in a potential GHG emission reduction of 16.7% and 21.6% respectively. Although a 20 kW and a 100 kW system will cost $ 2919 and $ 13,365 per tonne of fillets, it will potentially reduce the electricity bill by $1,071 and $7,377 per tonne of fillets per year in the regional processor and the city retailer respectively (Shetty, Personal Communication), resulting in a payback period of less than three years for the regional supply chain and two years for the city supply chain.

3.3.2. Biogas electricity

The filleting waste may also be utilised for biogas (a techno- logical modification and recycling waste CPS), providing a second alternative to grid electricity consumption.

Using the Buswell Equation (Symons and Buswell, 1933) and the amino and fatty acid breakdown of the fish species from Western Australia (Esteban et al., 2007; Khoddami, 2012; Ng, 2010), the CO2, CH4, ammonia (NH3) and hydrogen sulphide (H2S) from the anaerobic digestion process can be predicted.

Although the Buswell Equation assumes complete digestion, it can be used to predict the quantity of potential CH4 production. Both Davidsson et al. (2007) and Curry and Pillay (2012) calculated the actual methane yield compared to the predicted yield of municipal waste and found 76.7% and 74.9% respectively. If the average (75.8%) is applied to this study, processing all the filleting waste would produce 85.57 kg of CH4 (Table 6), resulting in 4757 MJ of energy per functional unit in both supply chains. However, if converted to electricity using a generator, only 46% of the energy is converted (Reedman, Personal Communication), leaving 607.9 kWh per functional unit, theoretically preventing a potential 12.0% and 2.5% of total emissions from the city and regional supply chains respectively.

As the firms in this study produce other products, the energy production from fish waste production would only supply 0.62% and 3.75% of the total energy consumed by the city retailer and regional processor respectively, saving $1598 and $2071 per year. As the system would require both a digester such as a stainless steel IBC ($2850) and a generator to convert the gas to electricity ($11 500), the potential electricity savings would take nine years and seven years to recover costs from the city retailer and regional processor respectively, making biogas a less efficient investment for the potential GHG and electricity cost reductions compared to the solar electricity option.

3.3.3. Refrigeration modification

The refrigeration emissions as a hotspot in this research, was a hotspot in other food industries including fresh pineapple (Ingwersen, 2012), fish on the boat (Svanes et al., 2011b; Va'zquez-Rowe et al., 2013; Ziegler et al., 2013), ice cream (Australian Industry Group, 2011) and butter (Büsser and Jungbluth, 2009). Thus, GHG from refrigeration is not just a seafood issue. However, none of these studies offered potential CPS other than increasing maintenance to reduce the impact.

Equipment maintenance, a ‘good housekeeping’ CPS, is one method to reduce the GHG emissions from refrigeration. Although the equipment in the current study is regularly serviced, any lapse can increase the current leakage by 2.5% from the display cabinets and walk-in cool-rooms used by the regional processor, regional retailer and city retailer (The Australian Institute of Refrigeration, 2012). Therefore, applying this potential 2.5% savings to the sup- ply chains measured by simple good housekeeping CPS potentially prevents an estimated 0.27% and 0.10% of GHG emissions from the regional and city supply chains respectively.

Another method of reducing the impact of the refrigeration gas GHG in the studied supply chains is to change the refrigerant used (both a ‘technological modification’ and ‘input substitution’ CPS). The supply chain partners have recently converted their systems from R22 to the more ‘environmentally friendly’ R404a refrigerant. Although there are refrigeration gases with little or no GHG avail- able such as ammonia, which would eliminate GHG emissions from refrigeration (ICF Consulting, 2003), refrigerant changes are expensive, particularly when the current R404a systems in the supply chains measured are new. For example, a quote for Sydney Fish Markets to change their refrigerants from R22 to HFC-134a would potentially cost $255.22 per tonne of seafood (Northern Prawn Fisheries, 2014; Sydney Fish Market, 2013). This cost included updating the plant, evaporators, pipework and warm glycol defrost, warm glycol circulation to replace door heater, labour, electrical and controls, refrigerant, contractors costs, contingency and warranty (Northern Prawn Fisheries, 2014). As changing the refrigerant requires complete equipment replacement, it is an expensive project that is unlikely to occur until the current refrigeration units require replacing.

Although changing the refrigerant would improve each supply chain's GHG emissions by up to 11.0% and 4.2% in the regional and city supply chains respectively, the capital cost of updating the equipment without any resultant change in profit is a barrier to change.

In summary, the GHG emissions from refrigerants can potentially be reduced using good housekeeping, technological modification and input substitution. Such changes can potentially reduce the total GHG emissions by up to 11.0% (Fig. 4).

3.3.4. Utilising waste

In the supply chains measured, there was 62.5% (by weight) wastage from filleting fish. By isolating this waste during processing and developing by-products from the specific waste streams, resources efficiency may increase by ‘recycling’ the waste, which is one of the CPS. Biogas production has already been discussed, but further possibilities for waste usage include fertiliser and hydrolysate.

Fish waste can be composted into fertiliser for a possibly inexpensive solution. Lo'pez-Mosquera et al. (2011) composted the fish waste with seaweed and sawdust, applying their composting method to the waste from Western Australia could potentially reduce the GHG by 5.8% and 1.2% from the regional and city supply chains respectively.

Fish waste is also a good source of hydrolysate (fish ground into liquid) that can be used for protein powders, fertiliser, and animal feeds. Aspmo et al. (2005) and Bhaskar and Mahendrakar (2008) only used the viscera and thus, only used 10.3% of the waste product. However, when all the fish waste is used as in Nges et al. (2012), the GHGs would potentially reduce by 5.8% and 1.2% from the regional and city supply chains respectively.

There are barriers to recycling waste that affect both supply chains. Firstly, the cost to transport the waste over 1000 km to the nearest capital city for processing is a major barrier. Secondly, many of the suggestions above require the purchase of capital equipment to convert waste to biogas, fertiliser or hydrolysate. Thirdly, due to the current size of both the regional processor and city retailer, a new premise will also be required for each supply chain to manufacture these recycled products, or potentially outsource them. Thus, further research is required into the feasibility, cost and exact GHG reduction in each supply chain in Western Australia.

Another consideration is that whilst reusing the all the fish waste to create another product can potentially reduce the current GHG emissions by up to 6.0% (Fig. 4), these calculations do not account for the GHG in producing the waste products (e.g. electricity consumption). Thus, further research is required into the GHG potential in recycling fish waste.

3.4. Overall improvement opportunities

Overall, if all CPS discussed were applied e installing solar power, maintaining equipment, changing the refrigerant and recycling the fish waste e the current GHG emissions would reduce potentially by 34.6% and 25.4% from the regional and city supply chains respectively (Fig. 4). If extrapolated to the total fish quantity from the North Coast Bioregion, this would be equivalent to a potential savings of 4.9 million tonnes of CO2 e eq from the regional supply chain or 16 billion tonnes of CO2 e eq from the city supply chain's processes.

The two supply chains measured differed mainly in their electricity consumption per functional unit. Although the city supply chain has more significant improvement opportunities through the CPS discussed, the regional supply chain has significantly lower GHG emissions. The regional supply chain has greater opportunity for reducing its current GHG emissions, particularly harvesting solar energy. Although recycling filleting waste into biogas does reduce grid electricity consumption, it is expensive for the quantity of electricity generated. Therefore, installation of solar energy is recommended. The city supply chain had more GHG emissions, particularly as the retailer had a large electricity consumption.

Both supply chains have the same barriers to solar energy installation. Although harvesting solar energy in both supply chains will reduce both GHG emissions and ongoing costs, neither the regional processor nor the city retailer own their own premises. Thus, negotiations with the building owners are required to set up a “green lease” where the lease agreement is set up to recover costs of the solar panels (Council of Australian Governments (COAG) National Strategy on Energy Efficiency, 2012). Despite these barriers, installation of solar panels will result in long term lower energy costs and reduced GHG in both the regional processor and city retailer.

Although replacing refrigeration equipment will also reduce current GHG emissions, the cost of replacing equipment so soon after installing R404a equipment is a large barrier. Therefore, it is recommended both supply chains continue (or increase) their refrigeration maintenance to reduce refrigerant leakage and pre- vent further GHG emissions.

Despite the quantity of waste disposed in landfill, it had a minimal GHG impact in both supply chains compared to electricity consumption. Although a potential profit can be made from recycling this waste, it will only reduce GHG emissions up to 5.8%. Thus, further research into the profit potential of recycling is recommended only for solid waste reduction purposes as opposed to potential GHG savings.

4. Conclusions and recommendations

This research was unique as it measured the GHG emissions in finfish production from a whole of chain perspective in Western Australia and included both refrigerants and fish waste emissions.

Electricity had the greatest GHG emissions in both supply chains (76% in the regional supply chain and 94% in the city supply chain). These emissions may be reduced by installing solar panels at the regional processor and the city retailer, resulting in a potential 16.7% and 21.6% respectively.

Other potential CPS discussed in this study (biogas production, refrigeration gas modification and recycling filleting waste) had minimal reduction in GHG emissions, but when combined with solar, a potential 34.8% and 25.4% from the regional and city supply chains respectively could be prevented.

The possible uses from recycling waste have been modelled include using all the waste to create fertiliser or hydrolysate. Using all the waste (including heads, skin, viscera and frames) instead of portions only, provides the best potential of reducing the GHG emissions by 5.8% and 1.2% from the regional and city supply chains respectively. Further research is required to model the effects of these recommendations in Western Australia.

Finally, the outcomes of this research will assist in the enhancement of the framework of the seafood supply chain by enabling stakeholders, including similar Western Australian finfish companies to restructure the supply chain with reduced GHG emissions by implementing CPS.

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Tables

Table 1 Studies of various harvest methods

Harvest method	Country	Reference
Trawl harvested fish	Spain	(Iribarren et al., 2010; Iribarren et al., 2011; Ramos et al., 2011; Vázquez-Rowe et al., 2010a)
	Denmark	(Ellingsen and Aanondsen, 2006; Schau et al., 2009)
	Norway	(Ellingsen and Aanondsen, 2006; Schau et al., 2009)
	Antarctic	(Parker and Tyedmers, 2012)
Purse seine	Spain	(Hospido and Tyedmers, 2005)
	Denmark	(Thrane, 2004)
	Norway	(Schau et al., 2009; Svanes et al., 2011a, b)
	Spain	(Iribarren et al., 2010)
Multiple methods within a fleet	Norway	(Schau et al., 2009)
	Denmark	(Thrane, 2006)
	Spain	(Vázquez-Rowe et al., 2011a; Vázquez-Rowe et al., 2010b, 2011b)
	Senegal	(Ziegler et al., 2011)
	Sweden	(Ziegler and Hansson, 2003; Ziegler et al., 2003)

Table 2 Categories of inputs and outputs in the supply chains measured

	Unit per tonne of fish fillet	**Regional Supply Chain**	**City Supply Chain**
Consumable Items			
Carton liners	kg	14.400	0.003
Checkout paper bags	kg	53.156	
Checkout plastic bags	kg		14.988
Detergent	kg	17.026	10.479
Esky	kg	81.304	
Fillet covers	kg	13.893	8.960
Grease	kg	0.310	0.310
Hand sanitiser	kg	6.219	0.833
Hand soap	kg	3.110	0.957
Hydraulic oil	kg	1.267	1.267
Lanolin grease	kg	0.001	0.001
Lug buckets/tubs	kg	7.724	7.724
Pallet wrap	kg	0.114	0.114
Paper to wrap purchase	kg	47.841	177.778
Paper towels	kg	14.222	20.741
Plastic bag for fillet	kg	13.821	14.815
Polypropylene bags	kg	2.038	2.038
Rope	kg	1.097	1.097
Rust rinse	kg	4.026	4.026
Thick gloves	kg	0.301	0.301
Water	kg	45208.487	2849.003
Energy			
Electricity	kWh	13918.228	91509.972
Diesel	kg	2851.156	2851.156
Transport			
Ship	tkm	153.493	153.493
Articulated truck	tkm	741.508	101.148
Refrigerated articulated truck	tkm		3384.800
Rail	tkm	60.505	5.934
Light commercial vehicle	km	470.838	396.533
Storage			
R404a refrigeration gas	kg	4.483	8.325
Waste			
Fish waste	kg	1666.667	1666.667
Waste recovered from landfill	kg	663.333	663.333
Energy recovered from waste	kWh	502.264	502.264

Table 3 Emission factors used

	Unit	kg CO_2 –eq	Reference
Energy			
Electricity	Per kWh	0.916	(Life Cycle Strategies Pty Ltd, 2012)
Diesel	Per kg	0.675	(Life Cycle Strategies Pty Ltd, 2012)
Batteries	Per kg	22.98	(Lankey and McMichael, 2000; Life Cycle Strategies Pty Ltd, 2012)
Transport			
Ship	Per tkm	0.02076	(Life Cycle Strategies Pty Ltd, 2012)
Articulated truck	Per tkm	0.1002	(Life Cycle Strategies Pty Ltd, 2012)
Refrigerated articulated truck	Per tkm		(Life Cycle Strategies Pty Ltd, 2012; Tassou and Ge, 2008)
Rail	Per tkm	0.0008760	(Life Cycle Strategies Pty Ltd, 2012)
Light commercial vehicle	Per km	0.4402	(Life Cycle Strategies Pty Ltd, 2012)
Storage			
R404a refrigeration gas	Per kg	3260	(Department of Sustainability Environment Water Population and Communities, 2012)
Waste			
Fish Waste	Per kg	1.39	(Curry and Pillay, 2012; Davidsson et al., 2007; Esteban et al., 2007; Khoddami, 2012; Ng, 2010; Symons and Buswell, 1933)
Consumable Items			
Carton liners	Per kg	1.949	(Nolan-Itu Pty Ltd, 2002)
Checkout paper bags	Per kg	0.5327	(Nolan-Itu Pty Ltd, 2002)
Checkout plastic bags	Per kg	1.949	(Nolan-Itu Pty Ltd, 2002)
Disposable gloves	Per kg	0.5572	
Detergent regional	Per kg	0.5193	(Life Cycle Strategies Pty Ltd, 2012)
Detergent city	Per kg	0.1342	(Life Cycle Strategies Pty Ltd, 2012)
Esky	Per kg	6.4136	(Life Cycle Strategies Pty Ltd, 2012)
Fillet covers	Per kg	0.5572	(Life Cycle Strategies Pty Ltd, 2012; Saeki and Emura, 2002)
Grease	Per kg	0.3890	(Life Cycle Strategies Pty Ltd, 2012)
Hand sanitiser	Per kg	0.3819	(Kim and Dale, 2003; Life Cycle Strategies Pty Ltd, 2012; Renouf et al., 2010)
Hand soap	Per kg	1.0170	(Bishai et al., 2013; Greene, 1996; Life Cycle Strategies Pty Ltd, 2012; Renouf et al., 2010; Vink et al., 2010; Vink et al., 2003)
Hydraulic oil	Per kg	0.4094	(Life Cycle Strategies Pty Ltd, 2012)

Lanolin grease	Per kg	0.3885	(Barber and Pellow, 2006; Hoare, 1974; Life Cycle Strategies Pty Ltd, 2012)
Lug buckets/tubs	Per kg	0.5572	(Life Cycle Strategies Pty Ltd, 2012; Saeki and Emura, 2002)
Pallet wrap	Per kg	2.532	(Nolan-Itu Pty Ltd, 2002)
Paper to wrap purchase	Per kg	0.5327	(Nolan-Itu Pty Ltd, 2002)
Paper towels	Per kg	0.4118	(Hapsari Budisulistiorini, 2007)
Plastic bag for fillet	Per kg	2.532	(Nolan-Itu Pty Ltd, 2002)
Polypropylene bags	Per kg	4.083	(Nolan-Itu Pty Ltd, 2002)
Rope	Per kg	4.083	(Nolan-Itu Pty Ltd, 2002)
Rust rinse	Per kg	1.084	(Berenbold and Kosswig, 1995; Life Cycle Strategies Pty Ltd, 2012)
Thick gloves	Per kg	0.0002427	(Saeki and Emura, 2002)
Water	Per kg	0.000317	(Life Cycle Strategies Pty Ltd, 2012)

Table 4 Inventory differences between supply chains

Regional Supply Chain	**City Supply Chain**
Consumable items	
Water bill included the neighbouring firm's consumption	Water bill was just for the retail stage
Packaged fillets in polystyrene eskies for transporting to the store	Filleted on site and had no reason to transport fillets
Provided paper bags for customer's convenience	Provided plastic bags for customer's convenience
Used less paper to wrap the fillets	Used more paper to wrap the fillets
Energy	
Used electricity to support storage in both processing and retail stages	Only one supply chain stage consumed electricity, but consumed 6 times the consumption of the regional supply chain
Transport	
Fish travelled 20 km in refrigerated van	Refrigerated truck travelled over 2000 km
Consumable items travelled over 2000 km to site	Consumable items purchased in city
Storage	
Displays fillets bunched up in display cabinet using less refrigeration gases per functional unit	Spread fillets out in display cabinet using more refrigeration gases per functional unit
Waste	
No difference	

Table 5 Monte Carlo Simulation uncertainty analysis (1,000 runs)

	Mean	**Standard Deviation**	**Standard Error of Mean**
Regional supply chain	18,500	516	0.000884
City supply chain	92,600	3580	0.00122

Table 6 Potential biogas yield in kg per functional unit

	Carbon dioxide	Methane	Ammonia	Hydrogen sulphide
Amino acids	166.00	64.89	36.00	3.08
Fatty acids	56.36	46.93		
Carbohydrates	2.84	1.03		
Total	225.20	112.86	36.00	3.08
Assuming 75.8% digestion	**170.74**	**85.57**	**27.29**	**2.33**

Figures

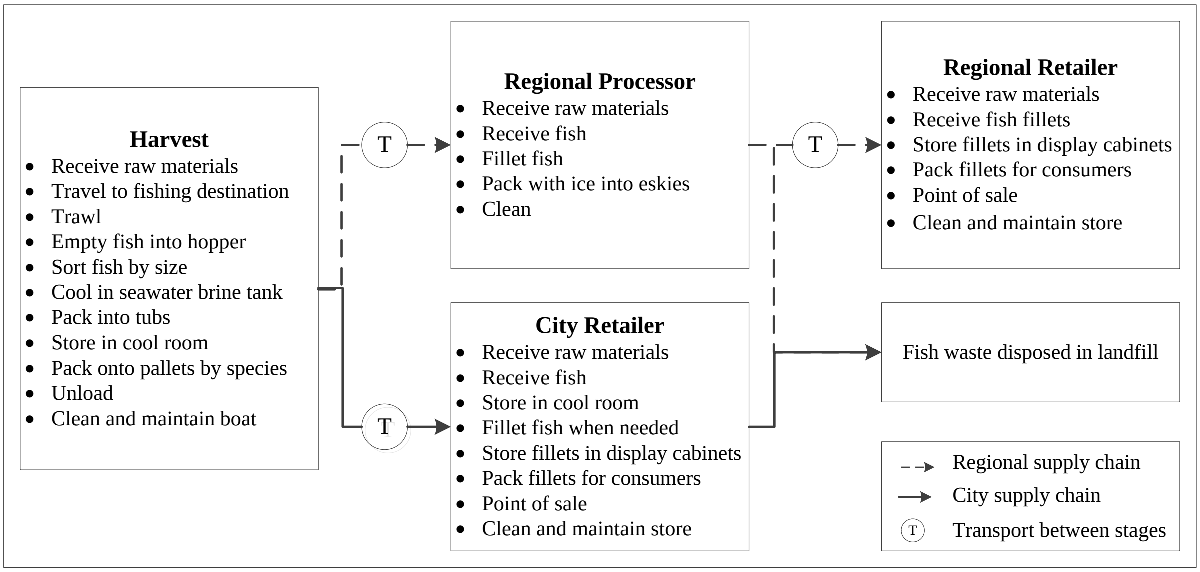

Figure 1 System boundaries of each seafood supply chain

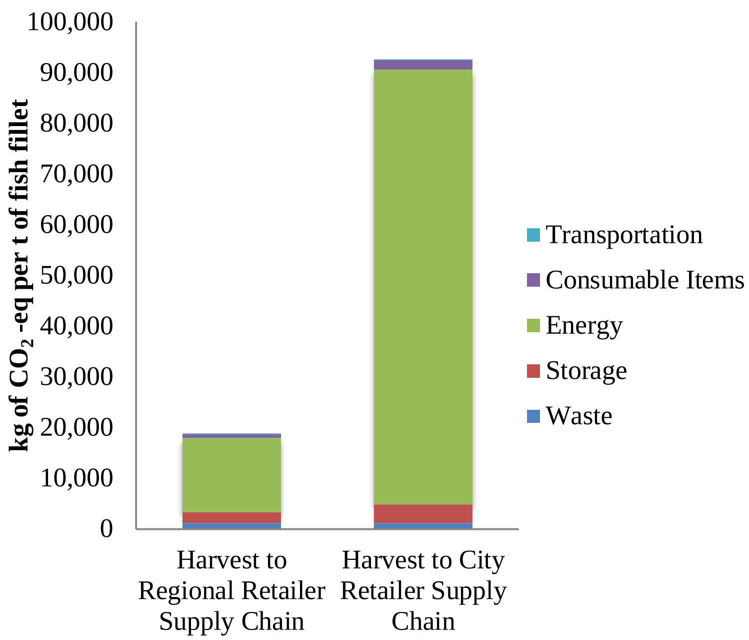

Figure 2 GHG comparision between the harvest to regional retailer supply chain and the harvest to city retailer supply chain

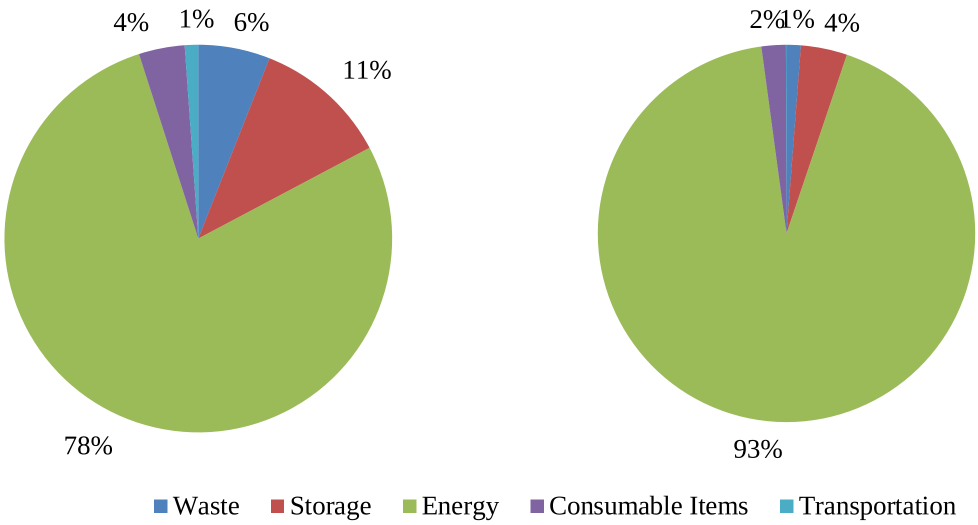

Figure 3 Distribution of GHG in the regional supply chain (left) and city supply chain (right)

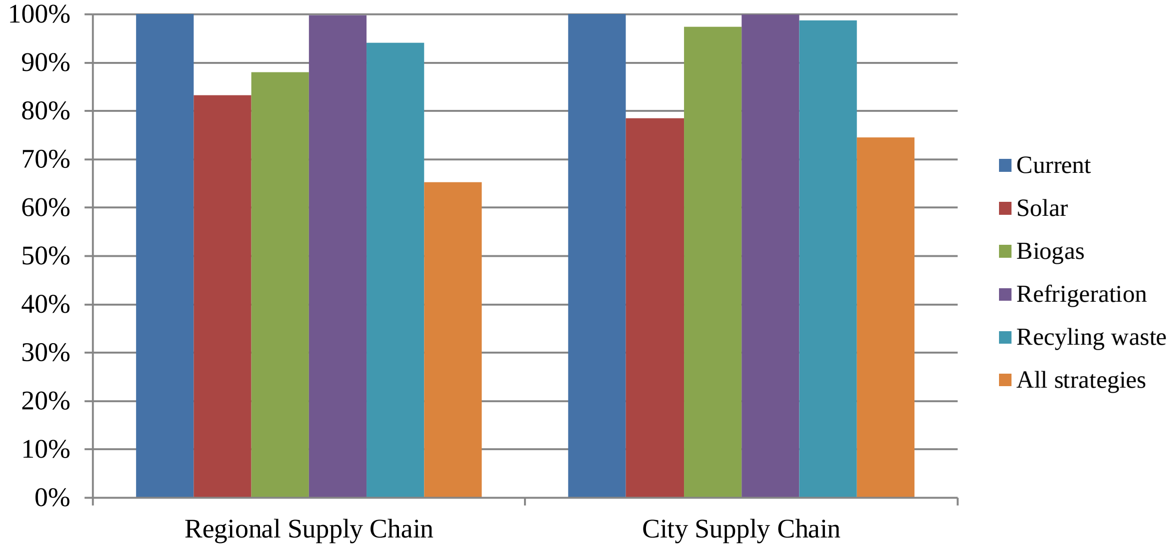

Figure 4 Percentage reduction of GHG from installing solar panels, utilising biogas, changing the refrigerant, recycling waste and a combination of the four CPS listed

CHAPTER 6. General Discussion

6.1. Introduction

This chapter summarises the thesis, primarily the results of Chapters 4 and 5 and discuss the implications of these results and relation to the thesis objectives (Figure 1.1):

1. Identify the areas of greatest greenhouse gas emissions from selected Western Australian seafood supply chains
2. Propose and model the impact of potential intervention strategies from the areas of greatest environmental impact on product quality and costs
3. Recommend intervention strategies to reduce the greenhouse gas (GHG) emissions from the Western Australian finfish supply chain.

This thesis measured the GHG emissions from three Western Australian finfish supply chains; a regional supply chain, independent supply chain, and major supply chain using a partial life cycle assessment (PLCA). Although the results from the three supply chain studies differed, the stage where the filleting occurred had the greatest GHG emissions or hotspots (regional processor, independent retailer and city processor). These emissions were primarily from electricity, filleting waste and refrigeration gases.

Potential cleaner production strategies (CPSs) were developed against these hotspots and assessed for their potential GHG reduction, impact on costs, and impact on product quality. Again, each supply chain differed, indicating there is no single solution to reduce the GHG emissions in the Western Australian finfish supply chain.

6.2. Significance of study

This study unique in combining environmental, economic and quality assessments in CPS development. As discussed in Chapter 2, no previous research had considered the impact of CPSs on the product quality and customers' expectations. For example, whilst removing fish heads and tails before transporting to increase the edible product portion reduced the environmental impact (Claussen et al., 2011; Thrane et al., 2009a), the customer (such as the retail outlet) would then receive a fish product with a reduced shelf life as the skin had been damaged. Therefore, by ensuring that the product still meets the customers' expectations after CPS implementation, the environmental impact may be reduced without effecting sales.

This was the first LCA study of the Western Australian finfish industry. As mentioned in Chapter 1, the Western Australian finfish industry have varying fish species and large distances to travel to the capital city Perth, differing from other Australian states and overseas processes.

The combined analysis of all the three supply chain stages in finfish production (harvesting, processing and retailing) is distinctive from other studies which focused entirely on either the harvest (Iribarren et al., 2011; Parker and Tyedmers, 2012a) or processing (Bezama et al., 2012; Thrane et al., 2009a), ignoring the retail stage. Similarly, there are very few Australian food retail (and no seafood) studies as most LCA research focusses on primary production (Renouf and Fujita-Dimas, 2013). Whole seafood supply chains have also been studied by Vázquez-Rowe et al. (2011b) and Winther et al. (2009), in the northern hemisphere, with different fish species, processes and emission factors from this study (as Chapter 2 described location to influence LCA results). Hobday et al. (2014) more recently performed a LCA on Australian rock lobsters, oysters, prawns and a finfish trawl supply chain. The finfish supply chain caught blue grenadier, tiger flathead and silver warehou (species not found in Western Australia) and processing did not include filleting and occurred in Melbourne and Sydney, so lacked the large transport distances associated with Western Australian products (Hobday et al., 2014). Unlike the current study, the retail sector was excluded.

This study also included inputs and outputs previously excluded in previous fish studies (Thrane, 2006; Vázquez-Rowe et al., 2011b). Both refrigeration gases and filleting waste were hotspots in this study and excluded in previous studies, thus in this case, providing a broader aspect of the supply chain than previously described. One reason for studies excluding filleting waste may be that they either sell fish whole, or already incorporate fish waste into their processes either directly or selling it (Ziegler et al., 2003).

The functional unit of one metric tonne of fish fillets provided unique results for Australian seafood. As discussed in Chapter 2, previous LCA studies are difficult to compare and apply elsewhere due to their functional unit definition. For example, this study's results differed from Hobday et al. (2014) who analysed the LCA of one kg of whole fish in a supply chain to restaurants rather than a supply chain (where fish were filleted) to a retail market. As the project objectives differed, the fish in Hobday et al. (2014) study were not filleted, excluding the filleting waste, packaging and the extra refrigeration gases and electricity from storage. Therefore, although these are both fish studies, by defining the functional unit as one metric tonne of fish fillets, the results shifted from the harvest as the area of greatest GHG emissions (Hobday et al., 2014), to the storage and display of fillets in this study.

The development of CPS and the modelling of their potential economic and quality implications for each supply chain sector brought a new aspect to seafood LCA studies. Whilst Bezama et al. (2012) measured the economic performance of CPSs implemented, this study provides the seafood industry with upfront implications, rather than retrospectively. The attention to the direct impact of CPSs on product quality is also unique to the seafood industry.

Consequently, this thesis provided an industry based approach, covering the Western Australian finfish industry, the whole supply chain including harvest, processing and retail, including components excluded from other finfish studies and modelling CPS implantation.

6.3. Main findings

The main findings of this study were the hotspots, opportunities to reduce them, and the industry implications of CPS application.

6.3.1. Hotspots

Electricity had the greatest GHG emissions in all three supply chain, followed by refrigeration gases, filleting waste and polystyrene eskies. Therefore, CPSs were assessed to mitigate each hotspot to develop economic opportunities that do not compromise on quality. As electricity had the highest GHG emissions in all three supply chains, solar electricity provided the most feasible and economical option to mitigate emissions.

6.3.2. Industry opportunities and implications

Whilst this thesis does provide an academic approach to an industry issue, results indicate opportunities for each Western Australian finfish supply chain stage.

Commercial fishing sector

Western Australian commercial fisheries are already implementing CPSs through eco-efficiency measures. As diesel is their highest cost (and greatest GHG hotspot in Chapter 4), efforts to increase output whilst reducing diesel consumption are in progress (Wakeford, 2010; Wakeford and Bose, 2013). Consequently, the harvest stage had the lowest GHG emissions in all supply chains measured (Chapter 4).

However, commercial fisheries in Western Australia (including other wild capture methods) can still increase their eco-efficiency and further reduce their GHG emissions by marketing current fish species considered as by-catch. By-catch are unwanted fish caught in the nets while fishing for other species and if not sold for human consumption, can then be used for fertiliser (López-Mosquera et al., 2011), biogas (Eiroa et al., 2012; Kafle et al., 2013), or hydrolysate (Aspmo et al., 2005; Bhaskar and Mahendrakar, 2008; Nges et al., 2012) as discussed for filleting waste in Chapter 5.

Processing sector

The processing sectors had the greatest GHG emissions in the supply chains measured, mainly from electricity consumption, refrigeration gases and filleting waste. Results from this study indicated the initial electricity consumption per metric tonne of fish fillets influenced both the areas of greatest GHG emissions and the effectiveness of the CPSs. For example, as the city processor had a smaller electricity consumption relative to the regional processor, variable speed drives and biogas production were less effective in GHG reduction than in the regional processor. When combining the PLCA, economic and quality results, solar electricity was the most effective CPS to implement in both processors, providing GHG reduction and the potential profit.

Whilst recycling fish waste into hydrolysate provided the highest potential profit for all sectors measured, further work is required to seek and maintain a market. Biogas production also provided a potential profit and GHG reduction, but until biogas becomes more prominent in Australia and specific systems are designed, they will require high maintenance and possibly release an unpleasant odour.

Retail sector

The retail sector had similar results as the processors discussed above. In this study, only the independent retailer filleted the fish, the regional retailer and supermarket received their fillets from the regional processor and city processor. As a result, the independent retailer had a much higher GHG emission than the regional processor and supermarket, reiterating that the filleting stage may produce more GHG emissions. Successful CPSs to reduce these GHG emissions were to utilise solar electricity and replace display cabinets with those using R134a refrigeration gas.

Retailers also have the power to put pressure on suppliers to improve the environmental impact. Styles et al. (2012) describes requirements retailers have used in Europe to minimise environmental impact, including supplier improvement programs, chemical restrictions, air freight bans and sustainable seafood sourcing. Whilst Styles et al. (2012) does place the onus of cleaner production pressure on the retailers, few of the situations discussed are GHG related. Retailers also have direct contact with consumers.

Consumers

Whilst the consumer stage of the supply chain was not covered in this project, they can still influence industry CPS implementation. Head et al. (2014) developed a phone app for consumers to make informed decisions about the environmental impact of the products they purchase with the intention of using consumers and their shopping habits to further influence industry to improve their practices.

6.4. External factors impacting GHG emissions

6.4.1. Location

Although the location of each facility was expected to influence the GHG emissions, results in Chapter 4 found transport to have a minimal impact. Instead, the location influenced the economic opportunities in CPS implementation as capital equipment could not be leased, and required expensive transport costs to deliver it to site.

6.4.2. Legislation

Current legislation has pushed the Australian seafood industry into replacing all refrigeration equipment using the R22 refrigerant (Department of the Environment, 2014b). This is to meet the Montreal Protocol (of which Australia is a signatory (UNEP, 2010)) aiming to reduce hydrochlorofluorocarbons (HCFCs) (such as R22) by 90 % in developed countries by 2015 (UNEP, 2012). As a result, many facilities have already upgraded their refrigeration equipment to avoid the price rise in R22. Consequently, if their equipment is owned rather than leased, replacing it again to reduce GHG emissions is not practical or economical. Therefore, current legislation to reduce HCFCs minimised the ability for many seafood facilities to further reduce their GHG emissions through their equipment. However, those facilities can still minimise the refrigerant leakage by maintaining the equipment (The Australian Institute of Refrigeration, 2012), and investigate equipment with low GHG emissions when the current equipment requires replacing.

6.5. Limitations

This project only covered one environmental aspect of the finfish supply chain – GHG emissions. Further seafood environmental analyses such as fish stocks were not part of this study. Currently, Western Australian fish stocks are managed by the Department of Fisheries who take annual data of quantities caught and remaining stocks in each area of Western Australia (Department of Fisheries, 2014). The opportunity of Marine Stewardship Council accreditation may provide further opportunities for each fishery to 1) maintain sustainable fish stocks, 2) reduce the environmental impact of fishing on non-target species and 3) implement an effective management system to maintain sustainability (Marine Stewardship Council, 2014). Thrane et al. (2009b) discusses the impact of eco-labels including MSC, concluding that managing fish stocks alone is not the only approach to fishery environmental management, but also involves managing the direct impact on the marine ecosystem such as fishing gear on the sea floor, and emissions such as GHG from both the fishery stage and on-shore supply chain. Therefore, Thrane et al. (2009b) recommended that MSC certification (as an established international eco-label) broaden to include further seafood environmental aspects, including the energy consumption from a LCA view.

Further emissions from the production of finfish were excluded from this study. Other seafood studies have measured eutrophication potential (EP) (Hobday et al., 2014; Hospido et al., 2006; Svanes et al., 2011b; Vázquez-Rowe et al., 2011b;

Ziegler et al., 2011) cumulative energy demand (CED) (Hobday et al., 2014; Svanes et al., 2011b), marine eco-toxicity (Hobday et al., 2014; Vázquez-Rowe et al., 2011b), ozone layer depletion (Hospido et al., 2006; Svanes et al., 2011b; Vázquez-Rowe et al., 2011b; Ziegler et al., 2011), photochemical oxidation (Svanes et al., 2011b), acidification (Hospido et al., 2006; Svanes et al., 2011b; Vázquez-Rowe et al., 2011b; Ziegler et al., 2011), photochemical ozone creation potential (POCP) (Ziegler et al., 2011), abiotic resources depletion potential (Hospido et al., 2006; Vázquez-Rowe et al., 2011b), and water use (Hobday et al., 2014). Whilst these methods provide a broader aspect to seafood sustainability and environmental impact, the aim of this project was to develop CPSs, and in the inventories developed in Chapter 4, chemicals that would add to these other environmental impacts were minor in comparison to the electricity consumption, refrigeration gases and waste.

In measuring the GHG emissions in this project, many emission factors were not available from an Australian database in the Simapro software. As energy consumption differs in each location (Duro et al., 2014), location influences the emission factors in each study. Within this study, emission factors that were not available on the system were taken from MSDSs and literature. Where emission factors were unavailable, energy breakdowns were used or the emissions were left at zero. For example, MSDSs indicated surfactants used in the bench spray, detergents and drain cleaners used in this study, but the only emissions from a surfactant that could be located was the energy used in secondary alkane sulphonate production (Berenbold and Kosswig, 1995). As a result, the emission factors used in this study could be improved by broadening the Australian emission database in the Simapro software.

6.6. Next steps

6.6.1. Functional unit

There is a need to standardise LCA methods so that results can be compared between studies. As discussed in Chapter 2, each LCA study is performed in isolation as functional units, system boundaries and country emission factors differ. As a result differing studies cannot be compared, and as identified in this study, hotspots and outcomes differed from previous supply chain studies.

6.6.2. Whole of chain

As this thesis identified potential CPSs for the Western Australian finfish supply chain, a follow up study measuring the actual GHG reduction following CPS implementation is recommended. As the seafood industry is ever changing – particularly in processing and retailing sectors – leaving the study at the current stage may result in a one off industry investment instead of modifying their overall approach to eco-efficiency. Additionally, a follow up study may also identify further GHG emissions that appear with industry expansion over time. For example, by minimising the electricity consumption, a chemical hotspot currently minimised by electricity consumption may hold a larger percentage of the total GHG emissions. For example, the independent retailer had such a high GHG emission from electricity consumption that refrigeration gases and filleting waste appeared minimal, but reducing that electricity consumption by implementing solar electricity may then highlight the refrigeration gas emissions and filleting waste as larger hotspots. As a result, it is recommended the current supply chain is followed up with a second PLCA study to encourage further CPS implementation in the Western Australian finfish supply chain.

6.7. Conclusion

In conclusion, this research found the processing stages that fillet fish, have the greatest GHG emissions within the supply chain, mainly from electricity consumption, refrigeration gases and filleting waste. Cleaner Production Strategies were designed to mitigate each hotspot, and while the economic opportunities differed between each supply chain, solar electricity provided the greatest potential greenhouse gas emissions and potential long tern profit in both the regional processor and independent retailer without compromising product quality. As a result of this study, the Western Australian finfish supply chain now has access to informed, cost effective opportunities to reduce their GHG emissions. The research findings provide a framework and strategies which are both sustainable and economically viable for industry and that can reduce total GHG emissions by 35%.

The strong industry interest by regional, city and independent processors for this research indicates that industries support sustainable strategies that have the potential to lower GHG emission and that there is a real commitment to examine the new technology used in this research.

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APPENDIX 1. Ethics Approval

Curtin University

Office of Research and Development
Human Research Ethics Committee

Telephone 9266 2784
Facsimile 9266 3793
Email hrec@curtin.edu.au
Web http://research.curtin.edu.au/guides/

Memorandum

To	Dr Janet Howieson, CESSH
From	Miss Linda Teasdale Manager, Research Ethics
Subject	**RD-47-10** Protocol Amendment and Extension Approval
Date	2 July 2012
Copy	Assoc Prof Alexandra McManus, CESSH

Thank you for keeping us informed of the progress of your research. The Human Research Ethics Committee acknowledges receipt of your Form B report, indicating modifications / changes, for the project "RD-47-10 Improving the supply chain for selected WA seafood". Your application has been ***approved***.

The Committee notes the following amendments have been approved:

1. Carry out a life cycle assessment on the various Western Australian fin fish supply chains. Interviews will be conducted with representatives from each company, and third parties such as suppliers and machinery manufacturers.

Approval for this project remains to **08-February-2013.**

Your approval number remains **RD-47-10,** please quote this number in any further correspondence regarding this project.

Thank you.

Miss Linda Teasdale
Manager, Research Ethics
Office of Research and Development

Curtin University

Office of Research and Development
Human Research Ethics Committee

Telephone 9266 2784
Facsimile 9266 3793
Email hrec@curtin.edu.au
Web http://research.curtin.edu.au/guides/

Memorandum

To	Dr Janet Howieson, CESSH
From	Professor Stephan Millett, Chair Human Research Ethics Committee
Subject	**RD-47-10** Protocol Extension Approval
Date	25 June 2013
Copy	Professor Alexandra McManus, CESSH

Thank you for keeping us informed of the progress of your research. The Human Research Ethics Committee acknowledges receipt of your Form B progress report for the project *"**RD-47-10** Improving the supply chain for selected WA seafood."*

Approval for this project is extended to **08-02-2014.**

Your approval number remains **RD-47-10.** Please quote this number in any further correspondence regarding this project.

Yours sincerely,

Professor Stephan Millett
Chair Human Research Ethics Committee

Curtin University

Memorandum

To	Felicity Denham
From	Wendy Jacobs
Subject	Protocol Approval **SPH-23-2014**
Date	15/05/2014
Copy	Vicky Solah

Office of Research and Development
School of Public Health
Human Research Ethics Committee

Telephone 9266 4346
Facsimile 9266 2958
Email w.jacobs@curtin.edu.au

Thank you for your "Form C Application for Approval of Research with Low Risk (Ethical Requirements)" for the project titled *"Cleaner production strategies to reduce greenhouse gas emissions in the Western Australian finfish industry"*. On behalf of the Human Research Ethics Committee, I am authorised to inform you that the project is approved.

Approval of this project is for a period of 4 years – 8/05/2014 to 8/05/2018.

Your approval has the following conditions:

(i) Annual progress reports on the project must be submitted to the Ethics Office.

(ii) It is your responsibility, as the Researcher, to meet the conditions outlined overleaf and to retain the necessary records demonstrating that these have been completed.

The approval number for your project is **SPH-23-2014.** Please quote this number in any future correspondence. If at any time during the approval term changes/amendments occur, or if a serious or unexpected adverse event occurs, please advise me immediately.

Kind regards

W Jacobs

Wendy Jacobs
Administrative Officer, Research Support
School of Public Health
Curtin University

Please Note: The following standard statement must be included in the information sheet to participants:
This study has been approved under Curtin University's process for lower-risk Studies. This process complies with the National Statement on Ethical Conduct in Human Research (Chapter 5.1.7 and Chapters 5.1.18-5.1.21).
For further information on this study contact the researchers named above or the Curtin University Human Research Ethics Committee. c/- Office of Research and Development, Curtin University, GPO Box U1987, Perth 6845 or by telephoning 9266 9223 or by emailing hrec@curtin.edu.au.

Research Project Information Sheet
Environmental supply chain management in the Western Australian fishing industry: Analysis, interventions and opportunities

About the project	The aim of this project is determine the environmental impacts and the effect they have on the operation costs and the product quality within the fish supply chain and provide alternative options to potentially reduce these impacts. The project is part of the larger project *Improving the supply chain for selected seafood species*.
The investigators	Dr Janet Howieson, Centre of Excellence Science, Seafood & Health, Ph. 08 9266 2034, j.howieson@curtin.edu.au Felicity Denham, Doctoral Student, Centre of Excellence Science, Seafood & Health, Ph. 08 9266 9761 f.denham@curtin.edu.au
Participants	Stakeholders in the fin fish value chain i.e. Harvesters, processors, wholesalers and retailers and their respective suppliers
Participant experience	The stakeholders involved will be interviewed by the doctoral student about the processes within their company and their product. Within each process, details of the name, quantities and cost of all resources used and all outputs produced (product, wastes, etc.) will be collected. These may be sourced from existing documentation, or measured by the student. The interview process will be scheduled at the convenience of the participant, either by telephone or at the site of the production facility. Follow up questions may occur via email and telephone. Participants may also be asked for product samples to provide a quality benchmark.
Participant rights and responsibilities	Participation in this project is completely voluntary; participants are at liberty to withdraw at any time without prejudice or negative consequences.
Handling of information	All data will be stored according to the State Record Offices requirements for a total of five years. All electronic data will be stored on a password protected computer. Only the doctoral candidate and supervisors will have access.
Results	All related results will be shared with the relevant participant once analysis is finished. Participants will only be identified in any published material as a number. The product or the location will not be identified without prior permission.
Complaints or concerns	If have any complaints about the way this research is being conducted you can raise them with the principle researcher, or if you prefer an independent person, contact the Human Research Ethics Committee at Curtin University.
Approvals	This study has been approved by Curtin University Human Research Ethics Committee (Approval number SPH-02-2014). The committee is comprised of members of the public, academics, lawyers, doctors and pastoral carers. Its main role is to protect participants. If needed, verification of approval can be obtained by writing to the Curtin University Human Research Ethics Committee. C/- Office of Research and Development, Curtin University of Technology, GPO Box U1987, Perth WA 6845, or by telephoning 9266 2784 or emailing hrec@curtin.edu.au.

We appreciate and thank you for your participation in this research

Research Project Consent Form
Environmental supply chain management in the Western Australian fishing industry: Analysis, interventions and opportunities

1. I have been given clear information (verbal and written) and have been given time to consider whether I want to take part. I am over 18 years.

2. I have been able to ask questions and they have been answered to my satisfaction.

3. I understand I may withdrawal from this study at any stage.

4. If I have any queries or concerns I know I can contact Felicity Denham (doctoral student) on 9266 9761 or Dr Janet Howieson (primary supervisor) on 9266 2034 at the Centre of Excellence Science, Seafood and Health, Curtin University.

5. This study has been approved by Curtin University Human Research Ethics Committee (Approval number SPH-02-2014). The committee is comprised of members of the public, academics, lawyers, doctors and pastoral carers. Its main role is to protect participants. If needed, verification of approval can be obtained by writing to the Curtin University Human Research Ethics Committee. C/- Office of Research and Development, Curtin University of Technology, GPO Box U1987, Perth WA 6845, or by telephoning 9266 2784 or emailing hrec@curtin.edu.au.

6. I have been given and read a copy of this Consent Form

I consent to take part in this research project

____________________	____________________	____________
Name of participant	Signature of participant	Date

APPENDIX 2. Questionnaires

2.1. Harvest

Inflows	Brand and size	Quantity per year	Transport of Materials to the Site		
			Supplier	Location	Mode
Water	N/A				
Ice					
Pallet wrap					
Disposable gloves					
Paper towels					
Carton liners					
Eskys					
Detergent					
Hand soap					
Hand sanitiser					

	Lifetime	Number required at a time	Weight of product	Quantity	Transport of Materials to the Site		
					Supplier	Location	Mode
Reusable gloves							
Aprons							
Boots							
Lug buckets/tubs							
Netting							

	Inflows	Units	Quantity purchased per year
Purchased Energy:	Electricity	kWh	
	Diesel	L	

	Species	Destination/s of waste disposal	Units	Quantity per year	Dead or Alive
By-catch:			kg		
			kg		

	Outflows	Units	Quantity per year
Products:	Saddletail snapper	t	
	Crimson Snapper	t	
	Blue Spotted Emperor	t	
	Total fish	t	

2.2. Regional processor

Inflows	Brand/type/size	Units	Quantity per year	Transport of Materials to the Site		
				Supplier	Location	Mode
Water	N/A	L				
Ice		kg				
Pallet wrap						
Disposable gloves						
Paper towels						
Carton liners						
Eskys						
Detergent						
Hand soap						
Hand sanitiser						
Reusable gloves						
Aprons						
Boots						
Lug buckets/tubs						
Caps						
Knives						

Inflows	Units	Quantity purchased per year	Cost per unit
Electricity	kWh		
Diesel	L		

	Outflows	Units	Quantity per year
Products:	Saddletail snapper fillets	t	
	Crimson snapper fillets	t	
	Blue spotted emperor fillets	t	
	Other fish	t	

Product	Destination	Mode of Transport	Distance km	Actual Load tonnes	Trips per year

2.3. Regional retailer

Inflows	Brand/type/size	Units	Quantity per year	Cost per unit	Transport of Materials to the Site		
					Supplier	Location	Mode
Disposable gloves							
Disposable hairnets							
Fillet covers							
Plastic bag for fillet							
Paper to wrap purchase							
Labels							
Checkout plastic bags							
Checkout receipt rolls							
Paper towels							
Hand soap							
Hand sanitiser							
Detergent							
Bench spray							
Drain cleaner							
Water							

	Inflows	Units	Quantity purchased per year	Cost per unit
Purchased Energy:	Electricity	kWh		
	Diesel	L		

Equipment Used	Equipment Lifetime	Equipment Model
Cool room		
Display cabinet		
Scales		
Checkout		

How long does the fish usually take to sell?	
How are the tubs transported back to the boats?	
What percentage of total sales are fish by quantity?	

2.4. Independent retailer

How much fish do you purchase per week?	
How long does the fish usually take to sell?	
How are the tubs transported back to the boats?	
What percentage of total sales are fish by quantity?	
What percentage of fish sales are fillets?	

Raw materials

Inflows	Brand/type/size	Quantity per year	Supplier
Gloves			
Disposable hairnets			
Fillet covers			
Plastic bag for fillet			
Paper to wrap purchase			
Labels			
Checkout plastic bags			
Checkout receipt rolls			
Paper towels			
Hand soap			
Hand sanitiser			
Detergent			
Bench spray			
Drain cleaner			
Water			

Inflows	Quantity purchased per year	Cost per kWh or L	Supplier
Electricity			
Diesel			
Gas			

Machinery

Equipment Used	Equipment Lifetime	Equipment Model	Supplier
Cool room			
Display cabinet			
Scales			
Checkout			

2.5. City processor

1. How many kg of finfish do you sell per year?

   ____

2. What percentage are fillets?

   ____

3. What is the average filleting yield?

   ____

4. What percentage of fillets are frozen?

   ____

5. How much other seafood do you sell per year? *(this is to split some of the answers bellow into approximate fish and seafood quantities)*

   ____

6. Where do the products go? *(this is to calculate the carbon footprint of transport)*

Destination	**Quantity of Fillets**	**Quantity of Whole Fish**

7. How many consumables do you buy per year? *(The supplier and brand are to assist me in identifying the ingredients involved and the weight consumed)* Please also specify if these are unique to fish.

Inflows	**Brand and size**	**Quantity purchased per year (or per month)**	**Supplier**	**Fish only?**
Hairnets				
Beard nets				
Disposable gloves				
Paper towels				
Pallet wrap				
Carton liners				
Vacuum bags				
Eskys				
Boxes				
Ice packs				
Labels				
Detergent				
Hand soap				
Hand sanitiser				

8. How much of the following utilities do you use*? (Electricity consumption may be a carbon footprint hotspot)*

Inflows	**Quantity purchased or Cost**	**Period of Time** (*e.g. 2 months)*
Electricity		
Gas		
Water		

9. How much refrigeration gas do you use and of what type? *(Refrigeration gases gave been found to be a carbon footprint hotspot. The type and quantity can be found near the motor)*

Equipment	**Quantity**	**Type of Refrigerant** (*e.g. R404a)*
Processing room cooler		
Cool room		
Freezer		
Ice machine		

2.6. Supermarket

What percentage of your fish are sold as fillets?	
Who are your fish suppliers?	
What percentage of your store sales are fish?	
What percentage of deli sales are fish?	
How much fish is thrown out per week?	
Filleting loss (if fillet on site)	
Expected drip loss?	
How long does the fish usually take to sell?	

Purchased Goods

Inflows	Brand/type/size	Supplier	Quantity	How often is it purchased?
Gloves				
Disposable hairnets				
Plastic bag for fillet				
Paper to wrap purchase				
Labels				
Checkout plastic bags				
Checkout receipt rolls				
Hand soap				
Hand sanitiser				
Paper towels				
Detergent				
Bench spray				
Drain cleaner				
Knives				
Aprons				
Refrigeration gas - Chiller				

Inflows	Brand/type/size	Supplier	Quantity	How often is it purchased?
- Display cabinet - Ice machine				

Inflows	Supplier	Quantity or total cost	Over what period of time	Percentage used for fish
Electricity				
Water				

Equipment

Equipment Used	Quantity	Equipment Model	Supplier (if known)	Time used per day	Electricity kWh
Cool room					
Display cabinet					
Scales					
Customer calling device					
Ice machine					
Checkout					

APPENDIX 3. Media

PIPELINE

MORE INFORMATION
Felicity Denham, Centre of Excellence
Science Seafood & Health, Curtin University
E: F.Denham@curtin.edu.au

Measuring supply chain emissions

Felicity Denham, Centre of Excellence Science Seafood & Health, Curtin University.

An exciting new project at the Centre of Excellence Science Seafood Health (CESSH) is underway to measure the carbon footprint of Australian seafood businesses. The PhD project, driven by increasing consumer interest in environmentally sustainable fishing, processing and retail practices, will analyse the potential savings businesses could make by decreasing carbon emissions.

Curtin University and Seafood CRC PhD student Felicity Denham has applied a life cycle assessment (LCA) tool to a finfish supply chain, encompassing the trawl, transport, processing and retail sectors. Results are divided into emissions associated with consumables, transport, energy and storage.

Application of the LCA to this chain has identified the current carbon footprint and areas of greatest impact within the supply chain. It has found that total carbon counts are similar to international results, but carbon “hot spots’ have been identified.

The next stage of the research is to identify strategies to reduce the environmental impact. These will be modelled to assess the impact on product quality and profitability, providing a holistic insight into potential improvements to current supply chains.

Australian Seafood Magazine September 2013

Seafood industry carbon footprint

FELICITY DENHAM PHD

Felicity is using the life cycle assessment tool to measure the environmental impact of the entire supply chain (ie from harvest to retail) of several Western Australian seafood businesses. The costs of these impacts to the businesses will be measured and cleaner production strategies recommended. Results so far have indicated the areas of greatest greenhouse gas emissions to be methane from fish waste, refrigeration gas leakage and polystyrene cooler production. Strategies to reduce these greenhouse gas emissions are under investigation.

RESULTS SO FAR:

- Calculated the quantity of carbon dioxide, methane and nitrous oxide (greenhouse gases) released in the process of harvesting, processing and retailing fish fillets..
- Found three major hotspots that release the most greenhouse gases and now investigating methods of reducing this:
    1. Recycling filleting waste, rather than disposing it, reduces the methane produced in landfill and provides a potentially saleable product.
    2. Refrigeration leakage leads to greenhouse gas emissions and can be reduced by maintaining equipment.
    3. Alternatives to using polystyrene coolers to store seafood, which do not compromise on product quality.

Australian Seafood Magazine July 2014

APPENDIX 4. Author Contributions

To Whom It May Concern,

I, Felicity Claire Denham, contributed 70 % of the planning, research, and writing to the paper/publication entitled "Environmental supply chain management in the seafood industry: past, present and future approaches" in the Journal of Cleaner Production.

Felicity Claire Denham

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Janet R Howieson

Vicky A Solah

Wahidul K Biswas

To Whom It May Concern,

I, Felicity Claire Denham, contributed 70 % of the planning, research, and writing to the paper/publication entitled “Greenhouse gas emissions from a Western Australian finfish supply chain” in the Journal of Cleaner Production.

Felicity Claire Denham

I, as a Co-Author, endorse that this level of contribution by the candidate indicated above is appropriate.

Wahidul K Biswas

Janet R Howieson   Janet Ho

Vicky A Solah   Vicky Solah