



# Life cycle assessment of salmon cold chains: comparison between chilling and superchilling technologies



H.M. Hoang<sup>a,\*</sup>, T. Brown<sup>b</sup>, E. Indergard<sup>c</sup>, D. Leducq<sup>a</sup>, G. Alvarez<sup>a</sup>

<sup>a</sup> Irstea, UR GPAN, 1 rue Pierre-Gilles de Gennes, 92761 Antony, France

<sup>b</sup> School of the Built Environment and Architecture, London South Bank University, Churchill Building, Langford, North Somerset BS40 5DU, UK

<sup>c</sup> SINTEF Fisheries and Aquaculture, Brattørkaia 17c, NO-7010 Trondheim, Norway

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## ABSTRACT

The cold chain is defined as a set of refrigeration steps that maintain the quality and safety of food product. Refrigerant leakage and the use of fossil fuels to produce electrical power for refrigeration equipment contribute greatly to ozone depletion and global warming. Thus, new and emerging refrigeration technologies are being developed to provide more energy efficient and environmentally friendly alternatives to current technologies. Superchilling is a concept where the temperature is reduced 1–2 °C below the initial freezing point of the product. The small amount of ice formed within the product (10–15%) serves as a heat sink, eliminating the need for ice during storage and transport. In this work, Life Cycle Assessment (LCA) is applied to the chilling and superchilling salmon cold chains. The superchilling cold chain presents an important improvement compared to the chilled one: diminution of about 18% of the environmental impacts. This improvement is mainly due to a better utilisation of available volume for transportation. Other solutions to increase the environmental performance (replacement/reduction of packaging material and diminution of electricity consumption during retail display) are also studied and a sensitivity analysis on the electricity grid mix of different countries is performed.

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## 1. Introduction

Worldwide it is estimated that 15% of the electricity consumed is used for refrigeration and air conditioning (IIR, 2005; Coulomb, 2008). Direct emissions from refrigerant leakage and indirect CO<sub>2</sub> emissions from combustion of fossil fuels to generate power for refrigeration equipment contribute greatly to ozone depletion and global warming. Maykot et al. (2004) estimated that indirect emissions contribute up to 95–98% of the Total Equivalent Warming Impact (TEWI) in both light commercial (i.e. integrals and vending machines) and household applications (refrigerator and freezer). New and emerging refrigeration technologies providing energy efficient and sustainable alternatives to current technologies have recently been developed for cold chain application. However, it is important to evaluate the environmental performance of these new technologies and assess the scope of improvements over conventional technologies.

Superchilling is a concept where the temperature is reduced 1–2 °C below the initial freezing point of the product (Claussen, 2011). The salmon is crust frozen in a blast freezer (Kaale et al., 2013). It is then allowed to equalize in temperature to give 10–15% ice throughout the product, which serves as a heat sink so that the additional ice normally added to chilled salmon is not required during storage and transport. Superchilled product presents improved quality such as extended shelf life, higher yield and reduced microbiological risk (Duun and Rustad, 2007). Drip loss is also significantly lower in superchilled samples of Atlantic salmon compared to chilled and frozen samples (Kaale et al., 2014). Compared to conventional technology, the superchilling process needs more energy to attain lower product temperature and some degree of freezing, but the energy used to produce additional ice is saved.

Life cycle assessment (LCA) is a standardized methodology (ISO 14044, 2006) for assessing the environmental aspects associated with a product, technology or activity based on the compilation of an inventory of material and energy inputs and outputs for each stage over a life cycle. A review of the main developments of LCA over the past 30 years in the domain of energy analysis was

\* Corresponding author. Tel.: +33 1 40 96 65 02; fax: +33 1 40 96 60 75.

E-mail address: [hong-minh.hoang@irstea.fr](mailto:hong-minh.hoang@irstea.fr) (H.M. Hoang).

### Nomenclature

COP	coefficient of performance
CP	corrugated plastic
DC	display cabinet
ECM	electricity country mix
EPS	expanded polystyrene
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
S	solution
SEC	specific energy consumption

given by [Udo de Haes and Heijungs \(2007\)](#). The LCA can be applied to compare two (or more) products and technologies. For example, [Ardente and Mathieux \(2014\)](#) used an LCA based approach for environmentally assessing the durability of energy-using products in order to identify when the potential extension of the product's lifetime could have life-cycle benefits. Two scenarios of different lifetimes of a target product and its potential substitution with better performing alternatives were compared. As an example of the application of LCA in the supply chain, the life cycle environmental impacts of ready-made meals manufactured industrially was compared by [Schmidt Rivera et al. \(2014\)](#) with meals prepared at home. The considered supply chain was built from several stages: preparation and pre-processing of ingredients, manufacture of meal, distribution and consumption. The authors remarked that the type of refrigerant used in the supply chain influences the impacts, particularly global warming and ozone layer depletion while the contribution of packaging is important for some impacts, including global warming, fossil fuel depletion and human toxicity. A comparison of the carbon footprint of one aspect of the supply chain, the food transport refrigeration systems, using different refrigerants (R404A, R410A and R744) was performed by [Wu et al. \(2013\)](#). In this study, the carbon footprint was calculated as the sum of direct emissions (by various greenhouse gas emissions and leakage in each process) and indirect emissions (the CO<sub>2</sub> equivalent emissions due to the energy consumption in each process). The results showed that the CO<sub>2</sub> emissions caused by the energy consumption are a large part of the total CO<sub>2</sub> emissions, thus increasing the coefficient of performance (COP) of the refrigerator and of other equipment can significantly reduce the energy consumption and emissions.

Recently, LCA has been applied to study the environmental impacts of the seafood industry. [Denham et al. \(2015a\)](#) analyzed and identified the most effective cleaner production strategies for improved environmental performance of the supply chain in the seafood industry. Many stages of the seafood supply chain were studied: production, transport, processing and packaging, storage and retail. It was recommended that in order to ensure the greatest reduction in environmental impact, a 'whole of supply chain management system' that incorporates life cycle assessment modelling should be used. The cumulative energy use, biotic resource use, and greenhouse gas, acidifying, and eutrophying emissions associated with producing farmed salmon in Norway, the UK, British Columbia (Canada), and Chile were reported by [Pelletier et al. \(2009\)](#). Only production was considered, not other cold chain steps (storage, transportation, distribution, etc.). The greenhouse gas emissions from two Western Australian finfish supply chains, from harvest to retail outlet, were measured using streamlined life cycle assessment methodology by [Denham et al. \(2015b\)](#). To our knowledge, the only previous LCA on chilled and superchilled

supply chains was carried out by [Claussen et al. \(2011\)](#). A comparative LCA study between chilled and superchilled haddock was performed and showed that the traditionally chilled fillets have approximately 23% higher impact potentials than the superchilled fillets for all environmental impact categories. They concluded that this diminution is a direct reflection of the ice content in the boxes (20% of mass for chilled haddock, no ice needed for superchilled haddock) and this is thus the most important parameter in this assessment. Transportation by truck and packaging material are the two biggest contributors to impact potentials in both systems, while the electricity used in the ice machine (chilled case) and in the Contact Blast Chiller (superchilled case) has only insignificant contributions. However, only the two first steps of the cold chain (production: preparation of the salmon in the factory and 1st transport: from the production to the distribution centre) were taken into account in this study and the impact of each step was not analyzed.

Up to now, an LCA study on a complete seafood cold chain has not yet been carried out. As an attempt to contribute towards further understanding of environmental impacts of this domain, the LCA approach is applied in the present work to compare the chilled and superchilled salmon cold chain; more stages (i.e. distribution centre, display cabinet, domestic fridge which were not studied by [Claussen et al. \(2011\)](#)) are considered so that the whole cold chain impacts can be analyzed and the most important steps can be identified. Moreover, this analysis allows the evaluation of the role of electricity in the chilled and superchilled cold chains. This parameter was considered insignificant in the first two steps (i.e. production and 1st transport) by [Claussen et al. \(2011\)](#) but it can have a greater contribution in "downstream" stages, in particular in the display cabinet in which an important quantity of electricity is needed. Other solutions to increase the environmental performance (replacement/reduction of packaging material and diminution of electricity consumption during retail display) are also studied.

## 2. Materials and methods

According to ISO 14044's framework, an LCA study consists of four steps:

1. Defining the goal and scope.
2. Life cycle inventory (LCI): modelling of product life cycle with environmental inputs and outputs (data collection)
3. Life cycle impact assessment (LCIA): understanding the environmental relevance of all the inputs and outputs.
4. Interpretation of the results.

### 2.1. Goal and scope of the study

#### 2.1.1. Goal of the study

As indicated in the introduction, the first goal of this study is to compare the environmental impacts of chilled and superchilled salmon cold chains. The inclusion of additional steps in the supply chain can potentially affect the results of the whole cold chain and thus the comparison between chilled and superchilled technologies. Moreover, it allows the identification of the most important steps of a complete salmon cold chain which is the second goal. The last goal is to test solutions that can reduce the environmental impacts of the cold chain by sensitivity analysis of different scenarios.

#### 2.1.2. Geographical and time limits

The salmon in this study is produced in Norway and transported to European countries. France is taken as the reference country for

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