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

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LIFE CYCLE ASSESSMENT OF SALMON COLD CHAINS: COMPARISON BETWEEN CHILLING AND SUPERCHILLING TECHNOLOGIES

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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 developed to provide better 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 because of the augmentation of available volume for transportation.

1. INTRODUCTION

Worldwide it is estimated that 15% of the electricity consumed is used for refrigeration (Coulomb 2008). Direct emissions from refrigerant leakage and indirect CO_2 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, comparison between conventional and new technologies is needed to evaluate the benefit of the new ones.

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. This crust will then equalise 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). 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 14040-14049) 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. The LCA can be applied to compare two (or more) products and technologies. A comparative LCA study between chilled and superchilled haddock from production to wholesaler was carried out by Claussen et al. (2011). In the present work, the same method is applied to the complete 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.

2. MATERIALS AND METHODS

An LCA study consists of four steps:
1. Defining the goal and scope of the study.
2. Life cycle inventory (LCI): Making a model of the product life cycle with all the 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.

The LCA study was performed using SimaPro software (version 7.3) with the CML 2 Baseline 2000 V2.05/ World 1990, one of the most widely used and acknowledged impact assessment methods (Claussen et al. 2011).

2.1. Goal and scope of the study

The goal of this study is to compare the environmental impacts of chilled and superchilled salmon cold chains. The traditionally chilled fish is packed in boxes filled with approximately 25 % ice to keep the temperature low during transport and storage. Superchilled fish contains 10-15 % ice.
The reference cold chains of chilled and superchilled salmon were reported in van der Sluis et al. (2012):

- they are composed of 7 steps (Table 1);
- among these steps, the chilled and superchilled salmon is processed differently (in terms of technology or temperature level) in the packaging and storage in the production step, in the 1st transport by refrigerated vehicle and the distribution centre storage.

Table 1: Steps of salmon cold chains and their duration (van der Sluis et al. 2012)

N°	Step	Duration (h)	Chilled vs Superchilled *Different* or Not
1	Production		
	- *Harvesting*	1.5	Not different
	- *Filleting*	not mentioned	Not different
	- *Packaging*	not mentioned	*Different*
	- *Storage*	24	*Different*
2	1st transport by refrigerated vehicle	36	*Different*
3	Distribution centre storage	12	*Different*
4	2nd transport by refrigerated vehicle	3	Not different
5	Display cabinet	96	Not different
6	Transport by consumer	not mentioned	Not different
7	Domestic fridge	48	Not different

2.2. Life cycle inventory (data collection)

In this section, the data of the input material and energy in each step per kg of salmon was collected.

2.2.1. Production

The production stage involves 4 main processes in which the farmed salmon is harvested, filleted, packed and stored before despatch. It is assumed that the harvesting and filleting processes are the same for chilled and superchilled salmon (van der Sluis et al. 2012) .

- Harvesting (data from Winther et al. (2009))

This process uses drum chilling and bleed chiller (both using refrigerated sea water). The inputs and outputs of this process are presented in Table 2.

Table 2: In- and outputs in salmon harvesting process

Input	Amount	Output	Amount
Live-weight salmon	1000 kg	Salmon, head-on, gutted	822 kg
Electricity	81 kWh	Salmon by-products to ensilage	178 kg
Carbon dioxide	0.15 kg		
Water	3500 litres		
Refrigerant R22	0.45g		
Refrigerant NH3	7.4g		

Ice	207 kg	

- Filleting

As the filleting is manual work, the energy consumption of this process is assumed to be negligible.

- Packaging

For chilled salmon, the salmon is chilled and packed with ice inside expanded polystyrene (EPS) boxes. Each box (0.66 kg of EPS) can contain 20kg fillets and about 5 kg ice (0.25 kg/kg salmon). Part of this ice (0.05kg/kg salmon) is used in cooling the fillets back down after some warming during preceding processing, but the remainder (0.2 kg/kg salmon) is available to keep the fillets cool during initial distribution and transport.

- The needed amount of EPS for 1 kg of chilled fillet is: 0.66/20= 0.033 kg /kg salmon
- The needed amount of ice for 1 kg of chilled fillet is: 0.25 kg/kg salmon
- Based on cooling of water from 10°C to 0°C, assuming the ice machine has a COP of around 2.5, production of ice at these ratios requires 0.25 * (4.187 * 10) + 334) / 2.5 = 37.6 kJ /kg salmon (Brown 2014).

For superchilled salmon, the salmon is cooled down by the contact blast chiller and also packed inside the same EPS boxes (0.66 kg EPS for 25 kg fillet), no ice is needed.

- The needed amount of EPS for 1 kg of superchilled fillet is: 0.66/25= 0.0264 kg
- The needed amount of energy for 1 kg of superchilled fillet (in the contact blast chiller) is 72 kJ/kg salmon (Claussen et al. 2011).

- Storage

For chilled salmon, the product is stored for 24h at 0°C before despatch (van der Sluis et al. 2012). Two published sources of typical energy use were compared. The first, Thrane (2004), gave the average energy use for a chilled storage facility at 0°C as 0.44 kJ/kg for the 24h. The second source (Evans et al. 2014) presented average values for Specific Energy Consumptions (SEC) for chilled and frozen cold stores, which are based on the volume of the stores. For chilled the average SEC was 56.1 kWh/m3.year. Assuming the store is 75% full and that the packing density for salmon is 0.5, the SEC figure can be attributed across all product in the store as 1.48 kJ/kg for the 24 hour storage period. Taking an average of the two figures gives a rounded up figure of 1.0 kJ/kg salmon.

For superchilled salmon, the storage prior to despatch is very similar to that in the chilled chain, but temperature is kept slightly lower at -1.7°C. This results in somewhat higher heat loads on the storage room and in a slightly lower COP for the fridge plant. Brown (2014) estimated that 1.2 kJ/kg is needed for the 24 hour superchilled storage.

2.2.2. 1st transport by refrigerated vehicle (data from Claussen et al. (2011) and Tassou et al. (2007))

After leaving the producer, the salmon is transported by lorry for 36 h. The salmon is maintained at +2°C (chilled) or -2°C (superchilled) in the vehicle. The SimaPro background process 'Operation, lorry 28t, full/CH S' was used as input in order to account for the additional diesel required (input as kg/h) and exhaust gases emitted, due to refrigeration; this process can be utilized as it does not matter what the engine is used for, whether it is transport or refrigeration.

For chilled salmon:

- Each lorry can transport 18 000 kg chilled salmon. So the transport time distributes for 1 kg salmon is: 36 h / 18 000 kg = 0.002 h (or 7.2 s) / kg salmon.
- Tassou et al. (2007) suggested a part-load diesel use of 0.5 to 1.0 litres per hour, as the diesel density is 0.832 kg/l, the average of these figures would be 0.62 kg/h.

For superchilled salmon:

- Each lorry can transport 23 400 kg superchilled salmon (the quantity is bigger than in chilled process because there is no ice to be transported). The transport time distributes for 1 kg salmon is: 36 h / 23 400 kg = 0.0015 h (or 5.5 s) / kg salmon.
- The cold production is provided by a diesel machine which consumes a little more than that of chilled salmon: 0.64 kg/h.

2.2.3. Distribution centre storage

The salmon is stored for 12h in the distribution centre. Although there may be scale factors, it was assumed for this comparative study that distribution centre cold stores are similar to the storage facilities in the production stage, so that for a duration of 12 hours, the energy use would be approximately 0.5 kJ/kg *for chilled salmon*, and 0.6 kJ/kg *for superchilled salmon*.

Note: After the distribution centre storage step, the superchilled salmon is assumed to have the same treatment as the chilled one.

2.2.4. 2nd transport by refrigerated vehicle
After leaving the distribution centre storage, the salmon is transported by lorry for 3 h at +2°C :

- Each lorry can transport 18 000 kg chilled salmon. So the transport time distributes for 1 kg salmon is: 3 h / 18 000 kg = 0.0002 h (or 0.6 s) / kg salmon.
- The cold production is provided by a diesel machine which consumes 0.62 kg/h

2.2.5. Display cabinet
A method for estimating typical retail display cabinet energy use was developed by Brown (2014) based on published Eurovent test data for various cabinet types and different temperature classifications. The energy values at these different temperatures were regressed to give a value at 5°C and a typical open-fronted multi-deck cabinet was selected for chilled foods. This type had a daily energy consumption of 10.4 kWh/m^2, with a total display area of $5m^2$ and a gross volume of $5m^3$. It was assumed that 65% of the gross volume was usable (based on measurements of several common models) and that 50% of the remaining net volume would actually be stocked with food. Using a packed salmon density of 500kg/m3, this results in each cabinet holding 812.5 kg. The duration of display specified in the reference cold chain is 96 hours, during which energy consumption would be 208 kWh. This is equivalent to 921.6 kJ/kg.

2.2.6. Transport by consumer
Representing the journey from the supermarket to the consumer's home, this block is unrefrigerated and therefore has no energy impact form a cold chain energy perspective. However, it would result in varying degrees of warming which would then have to be addressed by the domestic refrigerator.

2.2.7. Domestic fridge
A method for estimating typical domestic refrigerator energy use based on the thresholds for Energy Efficiency Indices used in the Energy Labelling Scheme (see EU Directive 2010/30/EU and Commission Delegated Regulation Number 1060/2010) was developed by Brown (2014). A typical A+ rated domestic refrigerator with a net volume of 150 litres was chosen, which would have a threshold energy (i.e. the maximum allowed under A+) of 123.2 kWh/year. Assuming the appliance was on average 50% full, and that the packed salmon density was again 500kg/m3, and as chilled salmon is a relatively short shelf-life commodity, a domestic storage duration of 48 hours was chosen, during which 0.67kWh of energy would be used, equivalent to 64.8kJ/kg.

The refrigerant leakage is also considered in this study. The refrigerant type and % of leakage per year (data from Winther et al. (2009) and van der Sluis et al. (2012)) are presented in Table 3.

Table 3: Energy consumption and refrigerant use in salmon cold chain

N°	Step	Refrigerant	Ref. leakage (%/year)
1	Production		
	- *Harvesting*	NH3 & R22	5
	- *Filleting*	NH3	5
	- *Packaging*	NH3	5
	- *Storage*	NH3	5
2	1st transport	R134a/ R404a	10
3	Distribution centre storage	NH3	5
4	2nd transport	R134a/ R404a	10
5	Display cabinet	R404a/R507	12
7	Domestic fridge	R600a	2.5

2.3. Cold chain simulation

The salmon cold chain was built using the collected data in LCI, its flowchart is presented in Figure 1: the lower step becomes one of the inputs of the higher step. In general, the chilled and superchilled cold chains use the same processes but with different quantity of materials and energy consumption.

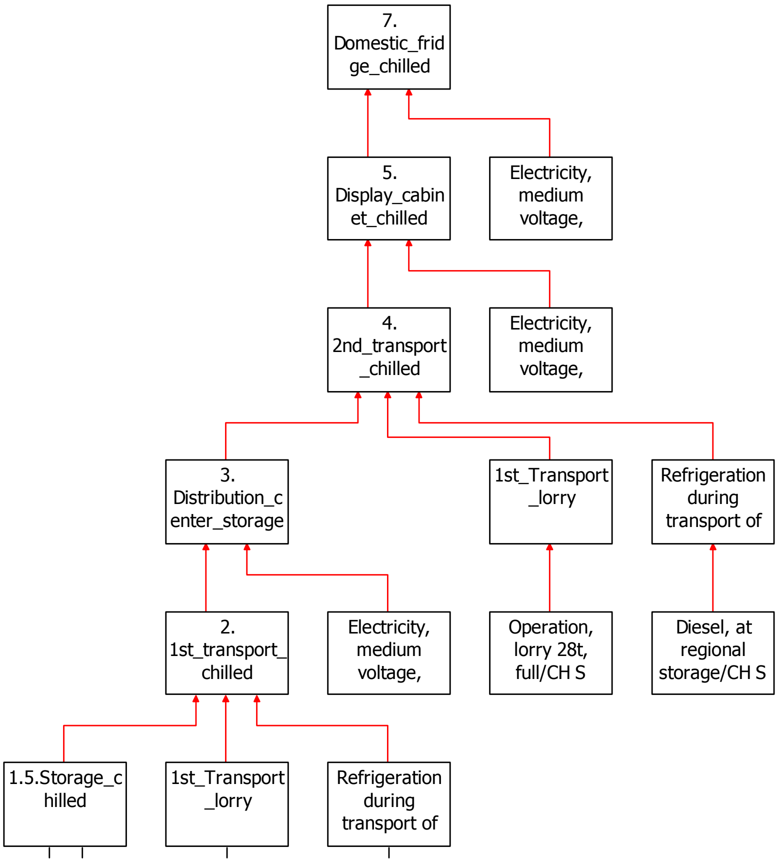

Figure 1: Flowchart of salmon cold chain

The LCA calculations are based on the compilation of the amounts of materials and energy used and the emissions associated with processes. The latter are multiplied with characterisation factors proportional to their power to cause environmental impact. One specific emission is chosen as the reference and the result is presented in equivalents with regard to the impact of the reference substance (Table 4).

3. RESULTS AND DISCUSSION

3.1. Comparison between chilled and superchilled salmon cold chain

The impact of chilled and superchilled salmon cold chain was assessed and compared. The results (Table 4 and Figure 2) show a net improvement in term of environmental impacts of superchilled cold chain compared to chilled one, with a diminution of about 20% in most of the categories: global warming (GWP100), ozone layer depletion (ODP), abiotic depletion and acidification.

Table 4: Environmental impact of chilled and superchilled salmon cold chain

Impact category	Unit	Chilled salmon	Superchilled salmon	Superchilled vs Chilled (%)
abiotic depletion	kg Sb eq	2.69E-03	2.17E-03	-19.3
global warming (GWP100)	kg CO2 eq	2.80E-01	2.27E-01	-19.0
ozone layer depletion (ODP)	kg CFC-11 eq	2.76E-08	2.22E-08	-19.7
human toxicity	kg 1,4-DB eq	9.36E-02	7.75E-02	-17.3
fresh water aquatic ecotox.	kg 1,4-DB eq	3.91E-03	3.48E-03	-11.1
marine aquatic ecotoxicity	kg 1,4-DB eq	3.52E+01	3.24E+01	-7.9
terrestrial ecotoxicity	kg 1,4-DB eq	7.24E-04	6.94E-04	-4.1
photochemical oxidation	kg C2H4	4.52E-05	3.71E-05	-17.9
acidification	kg SO2 eq	1.66E-03	1.34E-03	-18.9
eutrophication	kg PO4--- eq	2.61E-04	2.08E-04	-20.4

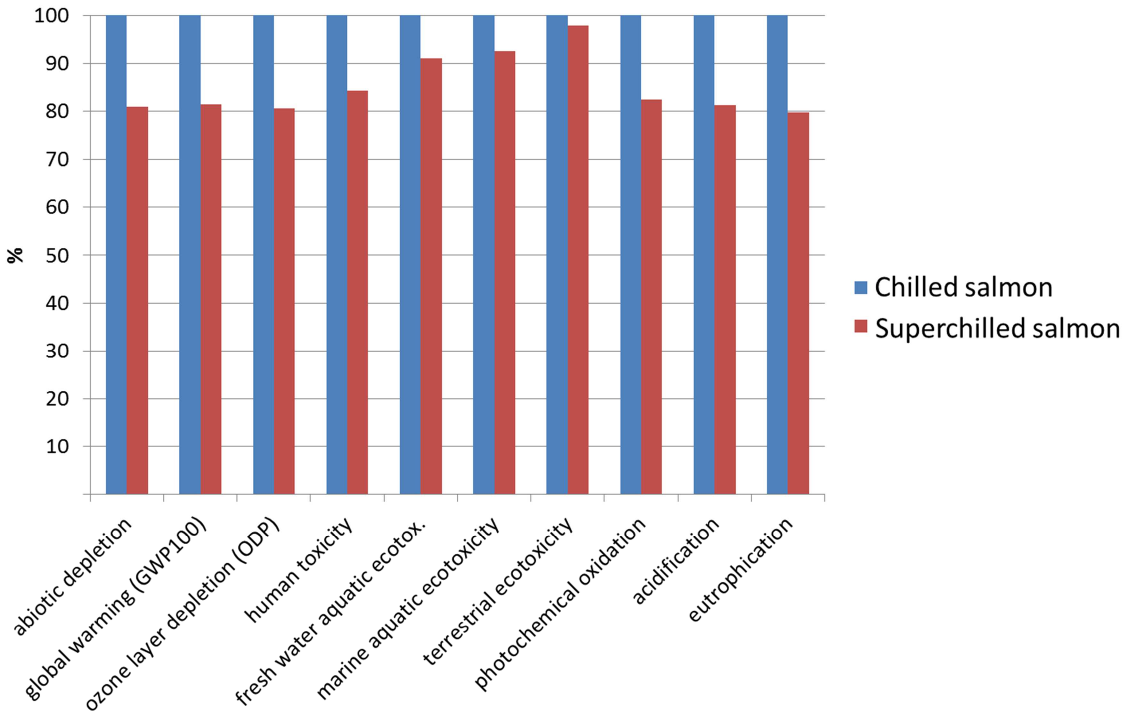

Figure 2: Relative comparison between chilled and superchilled salmon cold chain

3.2. Impact of cold chain steps

The impact of different cold chain steps concerning the global warming impact and human toxicity is presented in Figure 3. Compared to other steps, the 1st transport has the most important influence on the global warming because of the use of diesel while the production step has the greatest impact on the human toxicity because of the use of many natural and technical inputs, the expanded polystyrene EPS for packaging in particular. In general, the distribution center, the 2nd transport and the domestic fridge have small impacts while the display cabinet can have nearly the same influence as the 1st transport on the human toxicity (Figure 3) and other categories such as the abiotic depletion and the ozone layer depletion.

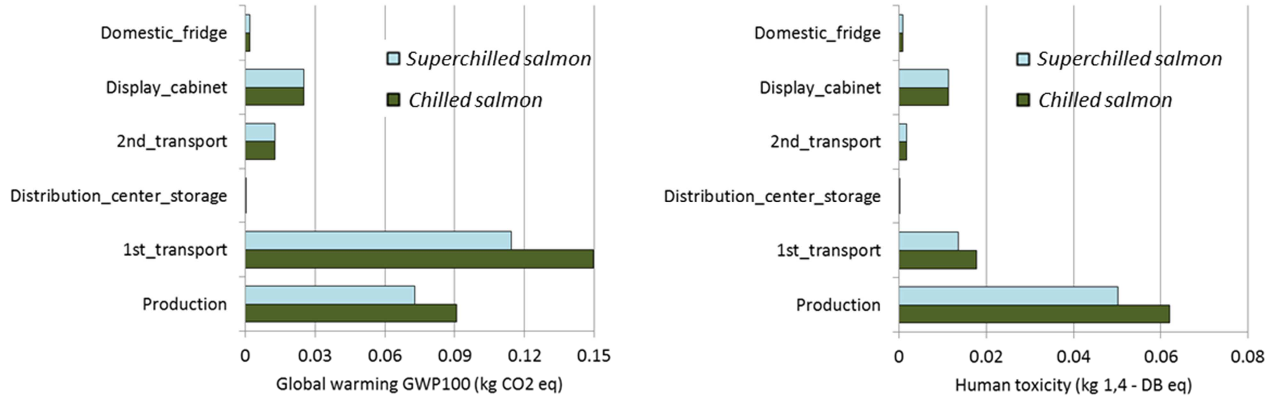

Figure 3: Impact of cold chain steps on global warming and human toxicity, comparison between chilled and superchilled cold chain

Compared to the chilled cold chain, the superchilled one presents an important diminution of the environmental impact in both production and 1st transport steps. This diminution is mainly due to the augmentation of available volume for transportation and the reduction of the quantity of needed EPS for packaging. As the downstream steps (2nd transport, display cabinet and domestic fridge) are assumed to be the same for the chilled and superchilled cold chains, they present the same impact.

It is to be emphasized that the production and 1st transport steps have the greatest environmental impact and energy consumption in the cold chain. As shown in Table 5, they represent from 36.2 to 90.2% of the cold chain total impact for chilled salmon and from 30.8 to 87.9% for superchilled salmon.

Table 5: Impact of the production and 1st transport steps against the total impact of the cold chain (in %)

Impact category	Chilled salmon (%)	Superchilled salmon (%)
abiotic depletion	90.2	87.9
global warming (GWP100)	85.9	82.6
ozone layer depletion (ODP)	88.3	85.4
human toxicity	85.4	82.3
fresh water aquatic ecotox.	54.2	48.5
marine aquatic ecotoxicity	36.2	30.8
terrestrial ecotoxicity	43.5	41.1
photochemical oxidation	82.8	79.0
acidification	85.7	82.4
eutrophication	89.6	86.9

4. CONCLUSIONS

Life Cycle Assessment (LCA) was applied to the chilling and superchilling salmon cold chains in order to compare these two processes and study their environmental impact. The superchilling cold chain presents an important improvement (diminution of about 20% in most of the categories) compared to the chilled one. This improvement is mainly due to the reduction of the quantity of needed EPS for packaging and the augmentation of available volume for transportation in superchilled case since no ice is needed.

5. ACKNOWLEDGEMENTS

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