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Comparative Life Cycle Assessment (LCA) of production and transport of chilled versus superchilled haddock (*Melanogrammus aeglefinus*) fillets from Norway to France

Ingrid C. Claussen[a*], Erlend Indergård[b], Magnus Grinde[c]

[a,b] *SINTEF Energy Research, Kolbjørn Hejes vei 1D, NO-7465 Trondheim, Norway (ingrid.c.claussen@sintef.no)/ (erlend.indergard@sintef.no)*

[c] *NTNU - The Norwegian University of Science and Technology, Department of Energy and Process Engineering Trondheim, Norway (magnugr@stud.ntnu.no)*

Abstract

Norwegian seafood products are important export products with regard to volume and value. More than 400 trucks of fresh fish products are weekly transported from Norway to European countries. The traditionally chilled fish is packed in boxes filled with approximately 30 % ice (equivalent to approximately 130 trucks) to keep the temperature low during transport and storage. Superchilled fish contains 10-15 % ice. The ice serves as a heat sink and thus, do not require use of ice during transport and storage. Compared with traditionally chilled foods, advantages related to superchilling are among others, extended shelf life, higher yield and reduced microbiological risk. Extended shelf life of superchilled products make it possible to sell a food product as fresh during a longer period of time. The results show that the traditionally chilled fillets have approximately 30 % higher impact potentials than the superchilled fillets for all environmental impact categories. This number is a direct reflection of the ice content in the boxes with chilled fillets, and this is thus, the most important parameter in this assessment. Transportation by truck and packaging material are by far 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) have only insignificant contributions. The results indicate the potential for saving in environmental impacts when switching from chilled to superchilled value chains. The truck export of fresh fish from Norway to Europe constitutes a potential for reducing the impact on global warming by approximately $78{\times}10^6$ kg of $C0_2$-equivilants per year. This corresponds to an annual emissions of roughly 24 000 cars.

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Keywords: Chilled; Superchilled; Haddock; LCA; Environmental impact; Production and Transport

* Corresponding author. Tel.: +47 73591641 ; fax: +47 73593950
E-mail address: ingrid.c.claussen@sintef.no

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1. Introduction

Life Cycle Assessment (LCA) is a standardized tool (ISO 14040-14049) that considers all environmental impact categories and all stages of the life cycle of a product, technology or activity. By maintaining a holistic perspective, LCA can deal efficiently with the issue of 'problem shifting' (i.e. solving one problem generates another) which is likely to occur if some impact categories or life cycle stages are neglected. An important aspect of LCA is to document the results in a credible and transparent manner.

In LCA one generally distinguishes between the foreground system and the background system. The foreground system is the life cycle activities for which specific data are collected in the study, while the background system typically represents the activities found in standard LCA databases. These databases contain life cycle inventories (LCI) on several thousand processes and products, and many of them are integrated in the commercial LCA software *SimaPro7.2*. *SimaPro* also holds many different impact assessment methods which are models used to convert emissions into environmental impact potentials. One of the most widely used and acknowledged impact assessment methods is the *CML 2 Baseline 2000 V2.05/ World 1990*, and for the Cumulative Energy Demand (CED) impact category the *CED V1.07* method can be included since this category is not included in the CML 2 Baseline method.

Europe has a large demand for Norwegian seafood products and expects high quality products. In order to maintain fresh products to the consumer, the suppliers must achieve temperature control during storage and transport. Fresh fish is normally packed in expandable polystyrene boxes filled with approximately 30 % ice. The ice keeps the fish chilled, but requires a lot of space which instead could be used to transport more fish. At the same time, the food industry is looking to reduce its environmental impacts. Reducing the total energy needed for conservation along the cold chain, without compromising quality, is the key motivation in developing new refrigeration technologies such as superchilling.

Superchilling is a concept where the product temperature is reduced 1-2ºC below its initial freezing point. This results in a so-called 'shell freezing' where a thin layer of ice is produced on the product surface during processing, while a small amount of ice formed within the product, serves as a heat sink. During storage, the ice equalize within the product. Familiar and well-known advantages related to superchilling are among others, extended shelf life, higher yield and reduced microbiological risk. Superchilled products do not require use of ice during storage and transport, as for fresh chilled fish. This is positive due to energy used for ice production, and more important to larger amount of fish loaded per truck which reduces the number of trucks. The main question that arises is if these benefits can compensate for the increased energy used in lowering the product temperature to minus 1-2ºC.

The objective of this work is to carry out an assessment using LCA methodology to compare the chilling and superchilling processes in terms of environmental performance. The production and transport of haddock (*Melanogrammus aeglefinus*) fillets from the processing facility in northern part of Norway to the wholesaler in France have been studied; fresh fillets chilled with ice and superchilled fillets.

2. Materials & Methods

A comparative LCA is performed in this study. Table 1 shows the environmental impact categories included in the LCA. Other non-environmental categories, such as economy, food quality and shelf life, are not included in the LCA.

Table 1. Environmental impact categories included in the LCA.

Environmental impact categories	Unit
Abiotic Depletion Potential (ADP)	kg Sb equivalents
Acidification Potential (AP)	kg SO_2 equivalents
Eutrophication Potential (EP)	kg PO_4^{3-} equivalents
Global Warming Potential (GWP)	kg CO_2 equivalents
Ozone layer Depletion Potential (ODP)	CFC-11 equivalents
Human Toxicity Potential (HTP)	1.4-DCB equivalents
Environmental impact categories	Unit
Ecological Toxicity Potential (ETP)*	1.4-DCB equivalents
Photochemical Oxidation Potential (POP)	kg C_2H_4 equivalents
Cumulative Energy Demand (CED)	MJ equivalents

*Includes fresh water aquatic ecotoxicity (FWAE), marine aquatic ecotoxicity (MAE) and terrestrial ecotoxicity (TE)

The system boundary between the two systems is shown in Figure 1. Mutual processes are ignored and thus, all upstream processes such as fishing operations, transport to processing facility, gutting and filleting is left out.

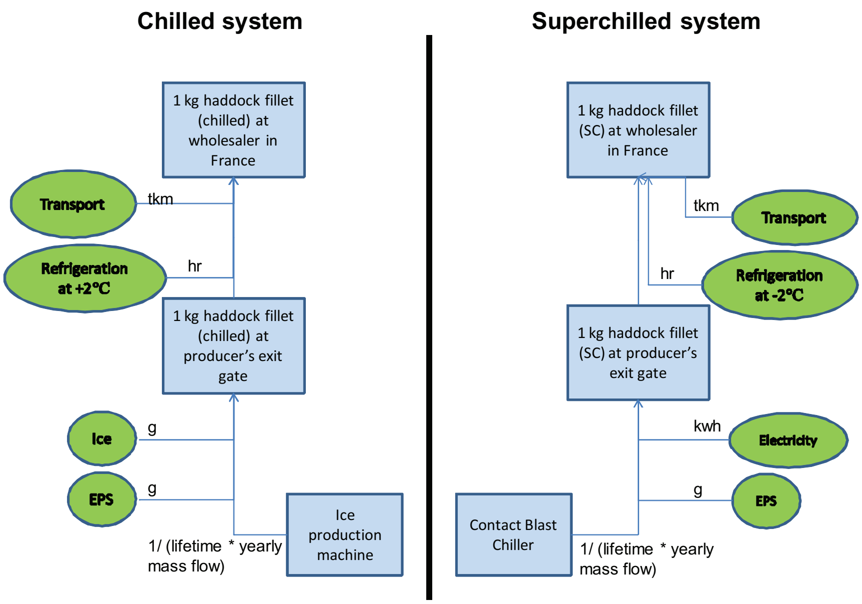

Fig. 1. Foreground system overview for chilled and superchilled production of haddock.

Accurate data on material and energy input in production of the refrigeration equipment used at the processing facility (i.e. Contact Blast Chiller (CBC) and the ice production machine) was not available. Capital foreground processes were therefore briefly assessed early in the study. Calculations showed that the equipment have minimal contribution to the final results, and is therefore left out from the LCA.

Capital costs were, however, included in the data from the LCA databases found in *SimaPro* (background system). Post processing transport to the wholesaler represents the end point of the studied system.

3. Results & Discussion

The functional unit utilized in this assessment is one kilogram fillet delivered to the wholesaler in Northern France. All results are expressed per functional unit (e.g. kg CO_2 equiv./ kg fillet).

Both chilled and superchilled haddock fillets are transported in expanded polystyrene boxes (EPS) with dimension 800x600x200 mm and capacity of approximately 26 kg. Ice content in the boxes was set to 0.3 kg ice per kg chilled fillet. The amount of fish in the boxes are 20 kg chilled fillet or 26 kg superchilled fillet. As the box consists of 0.660 kg EPS, 0.033 kg is allocated to each kilogram of chilled fillet and 0.02538 kg to each kilogram of superchilled fillet. One liter water and 0.064 kWh electricity is needed for the production of 1 kg ice.

A Norwegian electricity mix is utilized as the processing facility is located in Norway. Included in the background system are the electricity production in Norway and from imports, the transmission network and direct SF6-emissions to air. Electricity losses during medium-voltage transmission and transformation from high-voltage are accounted for. The electricity consumption in the CBC was calculated to 0.02 kWh per kg fillet.

Total distance (excluding car ferry transport) was estimated by Google Maps to 3334 kilometers. Total distance is multiplied by the transported amount needed per functional unit, i.e. 1.3 kg (chilled) and 1 kg (superchilled). The truck was assumed to be above 16 000 kg and representative for the average truck, with respect to age and technology, in the European fleet. Such an assumption is necessary to make in order to choose from the various process data sets found in *SimaPro*. Included background processes in *SimaPro* are; (1) operation of vehicle (production, maintenance and disposal of vehicles), (2) construction, (3) maintenance, and (4) disposal of road. During car ferry transport the refrigeration equipment uses electricity rather than diesel. For simplicity it is, however, assumed that the equipments runs on diesel the entire trip. Consequently, the calculated environmental impacts from refrigeration are in fact a little higher than the actual case. The superchilled fillets are kept at -2ºC during storage and transport, while the chilled fillets are kept at +2ºC. Leakage of cooling agents and diesel consumption in refrigeration systems used in transport are described in Winther et al (2009) [1]. Diesel consumption for two different systems is listed for the cooling system temperatures 0ºC and -20ºC. The system with the highest difference in diesel consumption at the two temperature levels was chosen. Furthermore, as the data were only given at 0ºC and -20ºC, linear relationship was assumed and diesel consumption was calculated (by inter- and extrapolation) to respectively 3.68 kg (at -2ºC) and 3.60 kg (at +2ºC) per hour. A diesel density of 0.84 kg/l was used to convert from liters to kg, as required by the background process data found in *SimaPro*.

The *SimaPro* background process *'Operation, lorry >16t, fleet average/RER U'* was used as input in order to account for the additional diesel required 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. The only thing that matters is how much input it requires (i.e. diesel) and how much it emits. However, since this process is normally used for transportation, *SimaPro* requires input with the unit of kilometers. The *SimaPro* process states that 1 km of operation requires 0.24931 kg diesel, i.e. 3.68 kg/hr / 0.24931 kg/km = 14.76 km/hr and 3.60 kg/hr / 0.24931 kg/km = 14.44 km/hr were therefore applied as inputs for refrigeration at -2ºC and +2ºC, respectively.

An annual leakage of approximately 5-10 % of refrigerant volume, a total refrigerant volume of 6.5 kg and 2500 working hours per year is reported in Winther et al (2009) [1]. R134a was chosen as refrigerants and maximum value for leakage (i.e. 10 %) was chosen in this study. The emission rate of R134a to air is equal to 2.6×10^{-4} kg per hour.

Due to the increased fillet capacity in a truck transporting superchilled fillets, the allocation of environmental impact potentials from refrigeration during transport onto each kg of fillet is slightly different. Winther et al., 2009 assumes load factors resulting in 18 000 kg of chilled fish per lorry. By compensating for increased fillet capacity, this corresponds to 23 400 kg of superchilled fillets.
Total transportation time from Norway to France is 55 hours. When allocating 55 hours of refrigeration onto each kg fillet (i.e. by dividing 55 with the respective load capacities) resulting in 0.00306 h (chilled) and 0.00235 h (superchilled) per kg fillet.

The environmental impact potentials from the electricity used in the superchilling process are minimal compared to the other foreground processes. The same applies to ice production in the reference system. Additional energy required to achieve superchilled properties, is assumed to be minimal when considering the total energy used in transportation. The electricity requirements are almost identical for both systems, i.e. 0.02 kWh/kg superchilled fillet and 0.0192 kWh/kg chilled fillets, as the chilled fillets requires 0.3 kg of ice per kg. The ice produced serves as a cooling agent (together with the cargo room refrigeration) during transport and some of it will melt along the way. The superchilled fillets, however, maintain their properties due to a lower temperature in the cargo room. In other words, the difference in direct energy consumption occurs in the refrigeration of the cargo room.

Table 2 shows the final comparative results for each environmental impact category per kg fillet delivered to the wholesaler in France. The column to the far right shows the reduction in impact potentials for the superchilled fillets relative to the traditional chilled fillets. When considering the increase in impact potentials for traditional chilled fillets relative to the superchilled fillets, the number will be approximately 30 % for all categories that is the same as the ice content in the boxes with chilled fillets.

Table 2. Final comparative results for chilled and superchilled case

Impact category	Chilled fillets	Superchilled fillets	Chilled versus superchilled [%]
ADP [Kg Sb equiv.]	0.005747466	0.004425848	-22.99
AP [Kg SO_2 equiv.]	0.003575559	0.002754412	-22.97
EP [Kg PO_4^3 equiv.]	0.000757892	0.000583938	-22.95
GWP 100 [Kg CO_2 equiv.]	0.69811906	0.53777862	-22.97
ODP [CFC-11 equiv.]	9.60E-08	7.40E-08	-22.96
HTP [1.4-DCB equiv.]	0.25043415	0.19283015	-23.00
FWAE [1.4-DCB equiv.]	0.035297284	0.027179697	-23.00
MAE [1.4-DCB equiv.]	75.661057	58.288065	-22.96
TE [1.4-DCB equiv.]	0.00129093	0.000999781	-22.55
POP [Kg C_2H_4 equiv.]	0.000124174	9.56E-05	-23.00
CED [MJ equiv.]	13.10448	10.11274	-22.83

The results were compared to the environmental impacts from car driving. The *SimaPro* process *'Operation, passenger car, petrol, fleet average 2010/km/RER'* represents the emissions from an average European car in 2010 per km, with a CO_2 emission rate of approximately 0.187 kg/km. Average yearly driving distance of a Norwegian passenger car in 2009 was 1.4×10^7 m [2]. By requesting an input of 1.4×10^7 m of this process, the average environmental impact potentials from a car during a year was calculated. The reduction in impact potentials per kg fillet, when replacing a traditional chilled system with a superchilled system, can be found by subtracting the columns in Table 3. If these figures are multiplied by 18 000 kg, which is the previously assumed load capacity of a single truck, the reduction per truck transport is given. This, however, premise an average route for all cars equal to Norway - France. Dividing these figures by the respective figures for an average car, the environmental impact reduction in terms of number of cars' annual environmental impacts, per truck transport is given. The results from these calculations are shown in Table 3.

Table 3. Potential reductions per truck transport using annual environmental impacts from a car as reference

Impact category	Reduction per year	Reduction per truck	Mean emission from one car [1 year]	Reduction in number of cars per truck [1 year]
ADP [Kg Sb equiv.]	0.001321618	23.789124	20.543708	1.2
AP [Kg SO_2 equiv.]	0.000821147	14.780646	7.9838263	1.9
EP [Kg PO_4^3 equiv.]	0.000173954	3.131172	1.09030631	2.9
Impact category	Reduction per year	Reduction per truck	Mean emission from one car [1 year]	Reduction in number of cars per truck [1 year]
GWP 100 [Kg CO_2 equiv.]	0.16034044	2886.12792	3.227.2018	0.9
ODP [CFC-11 equiv.]	0.000000022	0.000396	0.000444655	0.9
HTP [1.4-DCB equiv.]	0.057604	1036.872	999.37353	1.0
FWAE [1.4-DCB equiv.]	0.008117587	146.116566	42.549271	3.4
MAE [1.4-DCB equiv.]	17.372992	312713.856	211237.67	1.5
TE [1.4-DCB equiv.]	0.000291149	5.240682	2.453585	2.1
POP [Kg C_2H_4 equiv.]	0.000028574	0.514332	1.3802825	0.4

Table 4 shows the potential reduction in number of cars per year using annual environmental impacts from a car as reference. The potential for reducing the impact on global warming (GWP 100) is approximately 78×10^6 kg of CO_2 equivalents per year corresponding to an annual emission of roughly 24 000 cars.

Table 4. Potential reductions per year using annual environmental impacts from a car as reference

Impact category	Reduction per year	Reduction in number of cars per year
ADP [Kg Sb equiv.]	642306	31265
AP [Kg SO_2 equiv.]	399077	49986
EP [Kg PO_4^3 equiv.]	84541	77344
GWP 100 [Kg CO_2 equiv.]	77925454	24146
ODP [CFC-11 equiv.]	11	24046
HTP [1.4-DCB equiv.]	27995544	28013
FWAE [1.4-DCB equiv.]	3945147	92720
MAE [1.4-DCB equiv.]	8443274112	39971
TE [1.4-DCB equiv.]	141498	57670
POP [Kg C_2H_4 equiv.]	13887	10061

Table 2 shows that there is a clear linear relationship between the final impact potentials from the two systems. In Table 5 this phenomenon reappears as the relative contributions from most significant processes are almost identical for both systems. The reason for this is obvious when considering the foreground processes dominating the results, i.e. neglecting production of ice and electricity. Because of the difference in ice content in the boxes, there is a linear relationship between the two systems' need for packaging and transportation (30 % higher in the case of traditional chilled fillets). For the refrigeration during transport, the relationship is not strictly linear as different cooling temperatures require different fuel input, and cause different emission levels. However, these differences are relatively small and the linear relationship in capacity differences is also present here as each hour of refrigeration is allocated onto each kg fillet.

Transportation by truck and packaging material (i.e. EPS) are by far the two biggest contributors to impact potentials, in both systems as shown in Table 5. This implies that any further LCA work should focus on these foreground processes. Repeating the calculations for other scenarios such as e.g. domestic consumption or transatlantic consumption (requiring freight by ship or by air), should be done in order to test the generality of the results from this assessment.

Table 5. The biggest contributors from foreground processes to final impact potentials for chilled and superchilled cases

Impact category	Transport (truck)		Packaging (EPS)		Cooling (truck)		Ice/Electricity	
	Chilled	SC	Chilled	SC	Chilled	SC	Chilled	SC
ADP [Kg Sb equiv.]	69.3	69.2	26.0	26.0	4.6	4.7	0.1	0.1
AP [Kg SO_2 equiv.]	82.9	82.8	10.3	10.3	6.7	6.8	0.1	0.1
EP [Kg PO_4^{3} equiv.]	88.8	88.6	4.0	4.0	7.2	7.3	0	0.1
GWP 100 [Kg CO_2 equiv.]	78.0	77.9	15.7	15.7	6.2	6.3	0.1	0.1
ODP [CFC-11 equiv.]	91.6	91.5	1.8	1.8	6.6	6.7	0	0
HTP [1.4-DCB equiv.]	52.4	52.4	45.7	45.6	1.6	1.6	0.3	0.4
FWAE [1.4-DCB equiv.]	97.8	97.7	0.4	0.5	1.4	1.4	0.4	0.4
MAE [1.4-DCB equiv.]	95.6	95.5	1.0	0.9	3.0	3.1	0.4	0.5
TE [1.4-DCB equiv.]	93.5	92.9	2.0	2.1	2.5	2.5	2.0	2.5
POP [Kg C_2H_4 equiv.]	77.3	77.2	17.8	17.8	4.8	4.9	0.1	0.1

The Norwegian electricity production is dominated by hydropower, resulting in an electricity mix with quite low environmental impacts compared to the European electricity mix which have a high share of energy derived from fossil and nuclear source. A sensitive analysis is performed to investigate the assessment dependency on geographical location. In order to get any significant changes to the overall impact potential of the superchilled case, the electricity input was increased from 0.02 kWh/kg fillet to 0.2 kWh/kg fillet. The Norwegian electricity mix showed only a significant increase in terrestrial eco toxicity from 0.00099 kg 1.4-DB equiv./kg fillet to 0.00123 kg 1.4-DB equiv./kg fillet. When applying a European electricity mix, all categories experiences significant increases, and electricity replaced EPS as the second most important process in terms of environmental effects. However, the total impact potential is still significant lower than in the traditional chilled case for almost all categories. The exception is marine aquatic- and terrestrial eco toxicity which is slightly higher. For the traditional chilled case, the impact potentials increased slightly as the electricity mix applied in ice production also changed.

4. Conclusion

The results show that the reduced need for packaging and transport of ice in a system applying superchilling, will compensate for the environmental impacts of a significant higher energy demand in superchilled production. Chilled fillets have approximately 30% higher impact potentials than the superchilled fillets for all environmental impact categories. This number is a direct reflection of the ice content in the boxes with chilled fillets, and this is the most important parameter in this assessment. It should therefore be remembered that if the ice content were to change it can be expected that the results would change correspondingly.

The sensitive analysis showed that the electricity input for the superchilled system have to increase considerable in order for the traditional chilled system to be the most environmentally friendly option. Total impact potentials is not affected by the el-mix category (Norwegian or European) based on the sensitivity study. Thus, the additional energy required to achieve superchilled properties is minimal when considering the total energy used in transportation.

Transportation by truck and packaging material are by far the two biggest contributors to impact potentials in both systems.

The results indicated potential huge savings in environmental impacts from switching to superchilled value chains. The truck export of fresh fish from Norway to Europe constitutes a potential for reducing the impact on global warming (GWP) by approximately 78×10^6 kg of $C0_2$-equivilants per year. This corresponds to the annual emissions of roughly 24 000 cars.

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