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EXECUTIVE SUMMARY

This document provides an assessment of the environmental impact of several food supply chains through case studies, including the use of different packaging for fresh salmon, the comparison between imported and local apples, the use of air versus sea transport, the frozen cold chain temperature optimization and several alternatives for the last mile delivery. The ENOUGH tool, a greenhouse gas emission modelling software developed in the project[1], is used to evaluate the environmental performance of different practices and technologies. The results provided by the tool are compared with the conclusions of benchmark studies. The ENOUGH tool generally aligns with these results, allowing an easy comparison of different scenarios, quantification of impacts and identification of potential areas for improvements using a user-friendly software freely available on the web. We also identify improvement opportunities to reduce the environmental impact of food supply chains, such as using recyclable packaging, promoting short supply chains and using low-emission technologies. The main results of seven case studies were as follows:

Case 1: Reusing and recycling packaging

Polystyrene expanded (PS) is widely used in food packaging for fruit, fish and meat supply chains. If not recycled, PS emissions can reach 15% of the total emissions for fish products. By switching **to reused material or recycled material**, total emissions of the supply chain considered in this case study (Europe delivery) can be reduced by **10%**. An additional 61% reduction can be reached by selecting technologies already available in the market, leading to a **72%** global emission savings from the conventional chain using non-recycled PS packaging and current technologies.

Case 2: Imported apple vs local apple: is local always better?

Importing food products from locations like South hemisphere countries, when local grown products are also available, raises significant questions regarding environmental sustainability.

References and the simulations presented here consistently show that imported apples have a greater environmental impact than locally grown apples. This is mainly due to long-distance transportation which constitutes a significant portion of their carbon footprint.

Emission savings for the apple supply chain presented in this case study **can reach 90%** by switching to preferentially local grown products and using recycled packaging, floating condenser pressure and solar panels for cold storage, natural refrigerants and biomethane fuel for trucks, and electric cars.

Case 3: The high carbon footprint of air transport

Switching from air transport to sea transport for this case study, even if it multiplies the distance by 3, **reduces the emission** due to this long-distance transport **by 90%**. The additional emissions for the frozen salmon due to the freezing process and the low temperature transport conditions appear in this case negligible compared to the emissions savings by switching from air to sea transport. This **alternative to chilled salmon** shows a good potential in terms of CO_2 emission savings and quality criteria.

Case 4: Last mile delivery: a critical step in supply chains carbon footprint

The **Last Mile delivery** to the consumer can be very energy intensive compared to other transport stages. This is mostly due to the low load factor of vehicles and the predominance of private cars. By eliminating the physical store, **e-commerce is an alternative with a 22% reduction** compared to the hypermarket scenario. **Small local shops** help to reduce the emission impact of the last mile even more (**27% in this case study**) by promoting soft modes of transport such as walking and cycling.

For a supply chain like the yoghurt chain studied where **transport emissions are a major contributor**, and especially the home delivery stage, at least **38% emission savings can be reached** by switching to better logistic practices (e-commerce, local shops etc.) and a few low emission and available technologies (natural refrigerants, biomethane fuel, floating condenser pressure etc.). Even more savings could be reached by switching from plastic to low emissions materials for packaging, and reducing emissions from the production stage.

Case 5: Benchmarking of frozen food cold chains based on temperatures 3˚C warmer than current norms

Reductions in energy consumption and emissions for the warmer frozen cold chains were, as would be expected, achievable and useful for all product types. Emission savings ranged from 3.1% to 4.7% at -15°C and from 5.1% to 9.1% at -12°C. However, the **impacts on quality traits** varied with product type, with ground beef and spinach having significant reductions in quality in the -15°C chain, and what would perhaps be prohibitive reductions in the -12°C chain. Apple was less impacted but was still adversely affected.

From these results, raising frozen cold chain temperatures from -18°C to -15°C might be acceptable if some reduction in storage life is planned for. On the other hand, raising temperatures to -12°C may be a step too far, as reductions in quality retention were considerable. Vitamin C retention in spinach was the most extreme example of this, reducing from 208 days at -18°C to 105 days at -15°C and only 54 days at -12°C.

Case 6: Salmon supply chain in Norway

Norway is a major global salmon producer, with a complex supply chain including feed production, salmon farming, processing, and transport. Most Norwegian salmon is exported fresh to Europe and Asia, with a small portion sold frozen. This case study compared the ENOUGH tool to a SINTEF report, focusing on a salmon cold chain from Norway to Paris. The study found **areas for improvement in the ENOUGH tool, particularly in modelling processing steps and accounting for ice cooling during transport.** One major difference between the ENOUGH tool and the report investigated in this study is the ability of the ENOUGH tool **to take the food product quality into account.** This is seen as an important feature as ensuring that the quality is not worsened when implementing low emission technologies will be key for the industry.

Case 7: Replacement of salmon processing country

In this case study, the analysis shows that **transporting whole fish** requires more mass to achieve the same amount of edible product in Lithuania, leading to higher emissions. **By processing the fish closer to the point of origin and transporting only the final edible product,** companies can reduce the volume of goods transported, thereby lowering packaging needed, fuel consumption and environmental impact, reducing CO2 equivalent emissions by 47%. These emissions could even reach 63% by switching to packaging with lower carbon footprint.

Deliverable 4.2

1 INTRODUCTION

Based on data from the 2007-2016 period, emissions from the food systems represent from 21% to 37% of the total global GHG emissions[2]. A more recent study from 2021[3] reveals that the food system is responsible for around a third of global GH emissions (34%), with annual emissions estimated at 18 Gt of CO2 equivalent.

Sources of emission in food system come mostly from agriculture practices, land use mainly made up of carbon losses due to deforestation and the degradation of organic soils, energy related activities due to the intensification of mechanization in agricultural production, use of fertilizers and pesticides, but also from distribution activities (packaging, transportation, retailing…).

Although agriculture is a major source of GHG emissions, the food supply chain also plays a significant role. A breakdown of emissions individual contributions between those from agriculture before the farm gate, including emissions from land use, and those from food supply chain activities after the farm gate is presented in the IPCC report about climate change and land use[2]. Agricultural production is the main source of GHG emissions accounting for 10% to 14% of the global emissions, followed by emissions from land use at 5-14% and finally emissions from food supply chain activities beyond the farm gate at 5-10%.

It is important to note that the parts of the total emission allocated to production and to the supply chain can vary considerably depending on the food product, the farming practices used and the geographical location. For example, animal products, especially beef, tend to have a higher carbon footprint than plant-based foods, which reduces the share of food supply chain activities for them. Fresh vegetable and fruit emissions on the other hand tend to have a major contribution coming from transport activities.

Main sources of emission after the farm gate have been identified[3] as packaging (5.4%), transportation (4.8%), retail (4.0%), processing (3%) and domestic consumption (3%).

Packaging’s emissions come mainly from energy consumption during the production, but their impact on emissions is also highly related to reusing or recycling. The use of reused packaging or recycled material can potentially reduce the overall carbon footprint of packaging.

Although the concept of 'food miles' has attracted a lot of attention, transport only accounts for around 4.8% of food system emissions, roughly the same proportion as retail (4%). The majority of transport emissions come from road (81%) and rail (15%) transport, while sea and air transport account for only 3.6% and 0.4% respectively[3]. Distance, mode of transport, amount and type of product are key factors influencing the environmental impact of food transport. The concept of “food miles”[4] often refers to the distance that food travels between the farm gate and the place of consumption. Although distance is an important factor, the mode of transport, the amount transported, and the type of product must also be taken into account. There is a significant potential to reduce emissions through sustainable policies and practices, focusing on energy efficiency and the relocation of supply chains.

Retail is often mentioned as a major source of contribution in food supply chains, partly due to the intensive use of refrigeration, estimated to 25 to 50% of the global energy consumption[4], but also because retail outlets, particularly supermarkets, are very energy-intensive due to high requirements for lighting, heating and air conditioning. It is often mentioned that there is a considerable potential for retailers to reduce their environmental footprint by improving energy efficiency, adopting climate-friendly technologies and promoting sustainable practices. Studies[4] indicate that energy-related emissions can be reduced by 20-50% through proper selection and use of equipment, while refrigerant emission could be reduced by 80-90% using existing and emerging technologies.

While the contribution of food processing seems modest (3%), it is important to note that this figure has increased by 30% since 1990[3]. This significant increase underlines the growing impact of food processing on the climate. Energy consumption is a key driver of GHG emissions in food processing[5]. Studies[4] have shown that reducing energy consumption through more efficient technologies and sustainable practices, but also switching between energy sources can significantly reduce this sector's carbon footprint. For example, substituting fossil fuels with renewable energy sources in food has significant decarbonisation potential[4].

Source of emissions such as packaging and transport are partly dependant of the technologies used but are also highly related to logistic practices that sometimes should be questioned regarding their emissions.

One of the main purposes of this document is to suggest examples of better logistic practices and emission savings potentials through a few selected case studies. These are evaluated by simulating scenarios using the ENOUGH tool[1]. The potential of emission savings by switching to low emission technologies following the recommendations of WP2 roadmaps is also considered for every case study.

2 BENCHMARKING CASE STUDIES

2.1 Reusing and recycling packaging

2.1.1 Introduction

The packaging of food products is a significant issue in the supply chains, mainly because of the environmental impact of its production, use and disposal. Commonly used to protect fresh products, packaging made from non-biodegradable materials has a major environmental impact on our society. The intensive use of fossil raw materials has a highly damaging effect on the environment (depletion of resources, global warming, etc.). Packaging accounts for 39% of the consumption of petrochemical plastics in France[6].

One of the possible alternatives is the use of packaging made from biodegradable resources which offers potential benefits in terms of improving the environmental balance. The impact of material use is also highly dependent on recycling rates. For example, the recycling rate of expandable polystyrene (EPS) for packaging applications in Europe was 38 % in 2019 and several countries have committed to exceed 60 % in 2025[7] .

2.1.2 Case study description

The case study concerns the chilling salmon cold chain that considers the Norwegian salmon from the initial chilling and processing of the salmon, the refrigerated storage and transport to other European country up to the purchase and storage inside the domestic refrigerator. The building of the cold chain was done using the Enough tool and the data from [8].

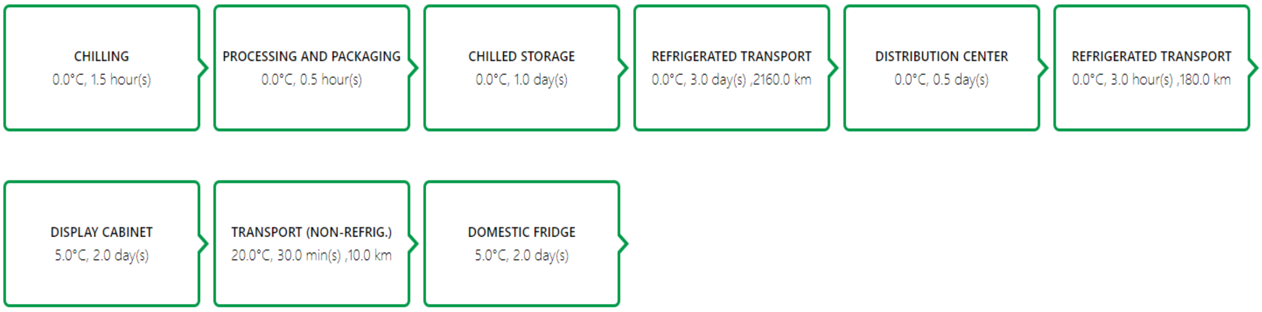


Figure 1: Building the salmon cold chain using Enough tool

Four packaging options were considered:

- Expandable polystyrene EPS box, 4 cm thickness: standard packaging for fresh fish transport
- Corrugated plastic CP box, 1 cm thickness[9]: light-weight tough material box which is produced from extruded corrugated plastic (polypropylene) sheets [10]
- Reused CP box, 1 cm thickness: this option simulates the reuse of CP packaging using a material with the same properties as CP but with a CO_2 emission factor 50% lower.
- Cardboard box, 1 cm thickness: cardboard is a biodegradable material currently used for frozen products[11], it is assumed that surface treatments or additional packaging (film) could be added so that it can be used to package fresh fish.

The main properties of the considered materials are summarized in the table below:

Table 1 Properties of packaging materials

Name	Thermal conductivity [W/(m.K)]	Density [kg/m3]	Emission factor [kg CO2/ton]
EPS	0.038	20	2950
CP[9]	0.027	140	1875[12]
Reused CP	0.027	140	938
Cardboard	0.05[13]	100	829

2.1.3 Simulation results, benchmarking the tool

Figure 2 presents the CO2 emissions of the salmon cold chain with the four options of packaging obtained by the tool. As the same cold chain was used, the impacts from refrigeration and transport are the same for the four options. The impact of packaging is lower than the impact generated by long distance refrigerated transport of 2340 km but still important in all cases: the CO2 emission by the production of packaging is greater than the CO2 emissions by using refrigeration equipment.

This result also highlights the possibilities to reduce the impact of packaging: by reusing the packaging or by using cardboard, a more environmentally friendly material. It is noted that reuse requires empty packaging to be transported and cleaned and is not yet practised for fish transport in many European countries. It therefore has an environmental impact of its own, as well as logistical cost and staff time constraints. In this case study, the option that generates the least CO2 emissions is the use of cardboard. It must be noted that, in a country where the PS recycling rate is close to 100% such as in Northern Europe countries with an emission factor evaluated to 750 kg CO2eq/ton, emissions[7] using PS would be similar to those of cardboard.

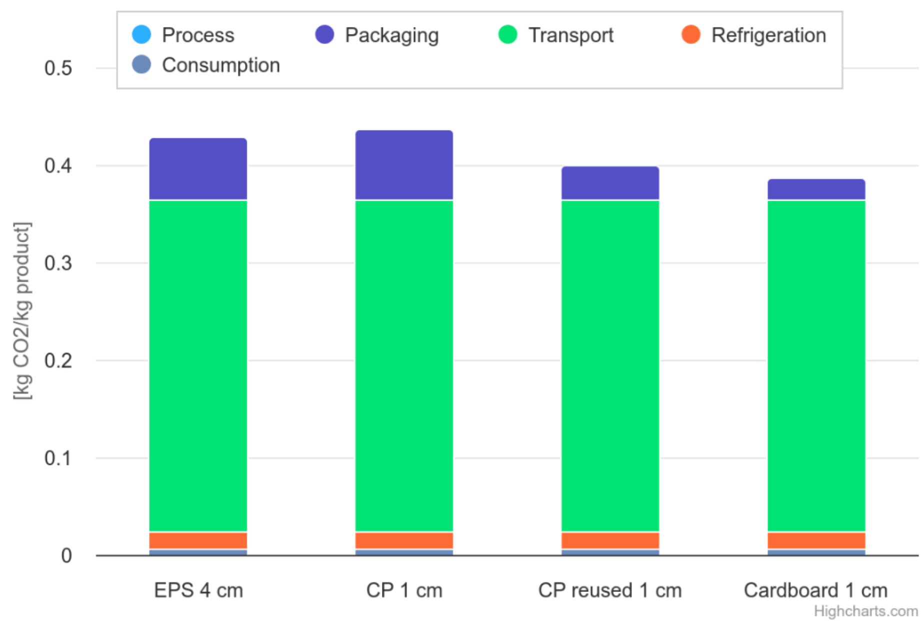


Figure 2: Benchmarking of the CO2 emission of salmon cold chain with different packaging

2.1.4 Reducing emissions with low emission technologies and practices

The supply chain presented in Figure 1 includes processing, storage and transport stages using current technologies. By simulating the use of technologies recommended in the WP2 roadmaps, it is possible to estimate the potential emission savings that can be reached with existing technologies selected for their high saving potential and positive payback times.

A list of these technologies suggested by the ENOUGH tool is presented below:

- A more efficient display cabinet (with a higher energy label) with closed doors
- The use of CO2 as refrigerant for the display cabinet
- The use of photovoltaic electricity for the retail store
- Floating condenser pressure for cold storage
- Biomethane as fuel for heavy transport trucks
- The use of CO2 as refrigerant in transport

Enabling these technologies in the simulation leads to a 61.4% emissions reduction (Figure 3):

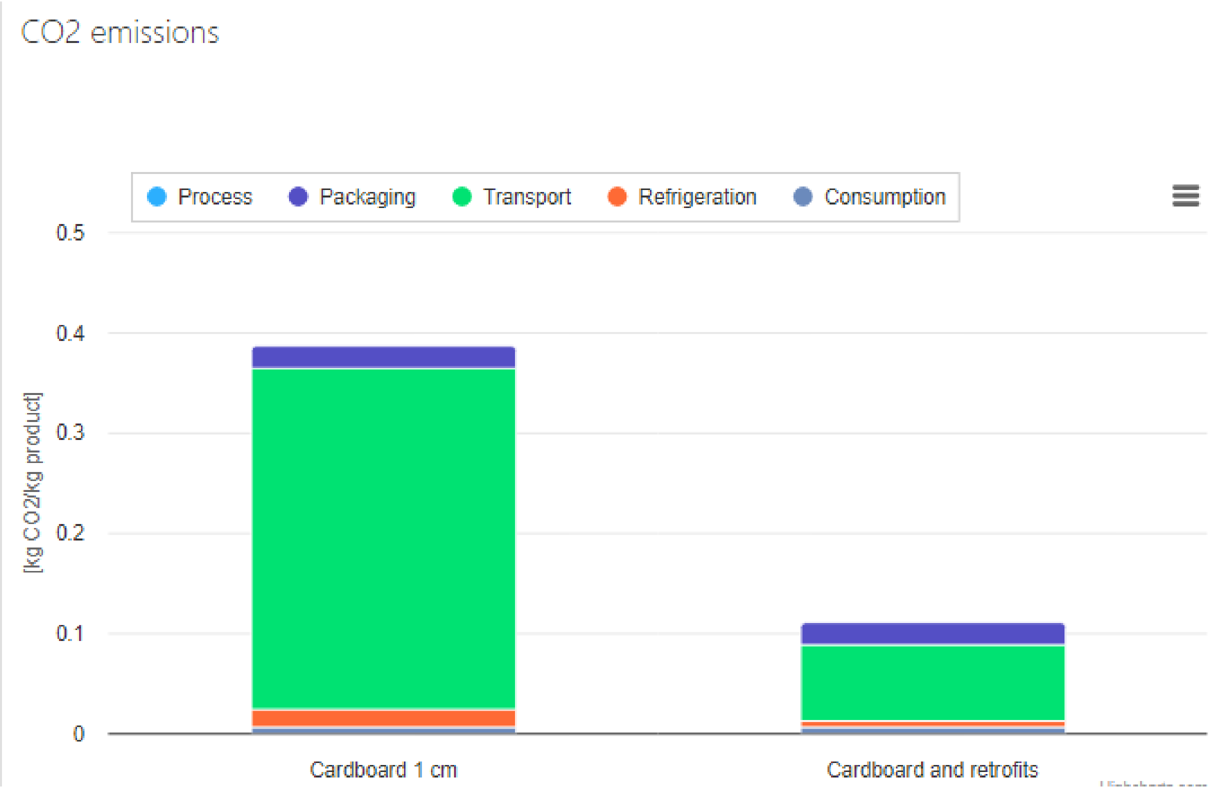


Figure 3: 61.4% emissions reduction for the salmon cold chain enabling WP2 roadmap technologies

Polystyrene expansed (PS) is widely used in food packaging for fruit, fish and meat supply chains. If not recycled, PS emissions can reach 15% of the total emissions for fish products. By switching **to reused material or recycled material**, total emissions of the supply chain considered in this case study (Europe delivery) can be reduced by **10%**. An additional 61% reduction can be reached by selecting technologies already available in the market, leading to a **72%** global emission savings from the conventional chain using non-recycled PS packaging and current technologies.

2.2 Imported apple vs local apple: is local always better ?

Climate change impacts of apples consumed within the country of production range in the literature from 0.2 kg CO2 eq for 1 kg of Swedish apples[14] to 0.6 kg CO2 eq per kg[15]. Goossens et al.[16] found a value of 0.4 kg CO2 eq per kg of BE apples. These values include the emissions from cultivation that count usually for 30 to 50%.

Several authors have highlighted that emissions from imported apples are 5 to 10 times higher. However, these apples constitute more than half of the apples sold in European countries such as Belgium or UK.

In Europe, apples are generally harvested in late Summer and Autumn. In New Zealand, apples are harvested between February and May, depending on the cultivar. This difference in seasonality partly explain that apples are imported during the Spring and Summer, even if European apples are available all year round thanks to the use of controlled atmosphere storage. In countries like UK and in Belgium, a large share of apples sold are originated from countries in the southern hemisphere[17].

Transport is a major contributor in the carbon footprint of apples. Non-european apples are transported by refrigerated cargo ship, which generate significant emissions, even if the amount transported by trip is very high. This refrigerated shipping more than triples the total impact of the Belgian apple supply chain and accounts for 46-59% of primary energy consumption.

It is important to note that estimates of energy consumption and emissions from shipping vary considerably from one study to another. This is often due to the lack of reliable data about vessel type, vessel size category, fuel use, and assumptions about the energy required for refrigeration.

2.2.1 Case study description

The case study here is originated from a paper from Goossens et al. published in the International Journal of Life Cycle Assessment[16]. Using apple consumption in a supermarket in Belgium and the share of Belgian (BE) and New Zealand (NZ) sales (Figure 4) as a case study, the authors compare the environmental impacts of BE and NZ apples taking into account packaging, the time of the year and food losses through the supply chain. The study suggests that, in terms of environmental impact, the transport of overseas apple should be discouraged. They also determine the most important factors influencing the environmental footprint of apples. The results show the impact of BE apples is systematically lower than that of NZ apples due to transport, whatever the time of the year. In addition, they show that a better choice of packaging could minimize even more the emissions.

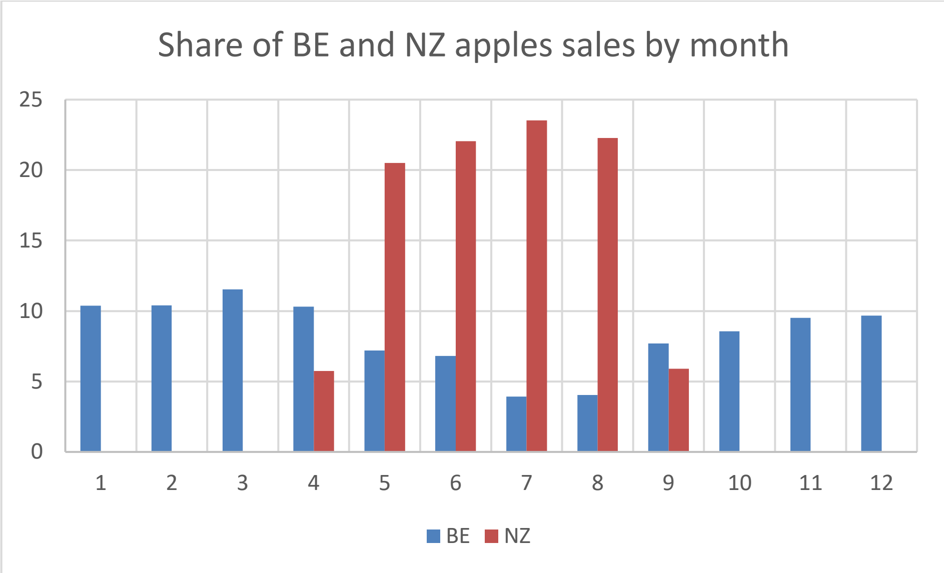


Figure 4: Shares (%) of BE and NZ apples sold per month throughout the year (source Colruyt group)

The primary data for this case study were collected using questionnaires sent to various stakeholders in the food chain such as farmers in New Zealand and Belgium providing information on harvest, storage and sorting processes, import and export companies, auction, and the retailer (Colruyt group). The data include cultivation practices, storage, sorting, distribution, packaging and consumer behaviour.

The case study simulated here starts from the farm gate and includes[16]:

- Controlled atmosphere storage (1°C, optionnal, only after October)
- Transport by ships for New Zealand apple (route from 21000 to 29000km over 28 to 33 days)
- Transport by truck to distribution center (DC)
- Storage in DC (1 day)
- Retail transport
- Storage in retail (cold room at 7°C, 1 day)
- Purchase by the consumer and transport
- Storage in fridge (average of 3.5 days)

The supply chain varies with the season. In October, Belgian apple are not stored in controlled atmosphere, but sold directly at retail. In March, New Zealand apples are stored in cold rooms without controlled atmosphere for 2 weeks after harvest, then shipped to Belgium. During the approximately 4-week sea transport, apples are not stored in controlled atmosphere, but only refrigerated. Upon arrival in Belgium, the apples can be stored in cold rooms without controlled atmosphere for up to 8 weeks.

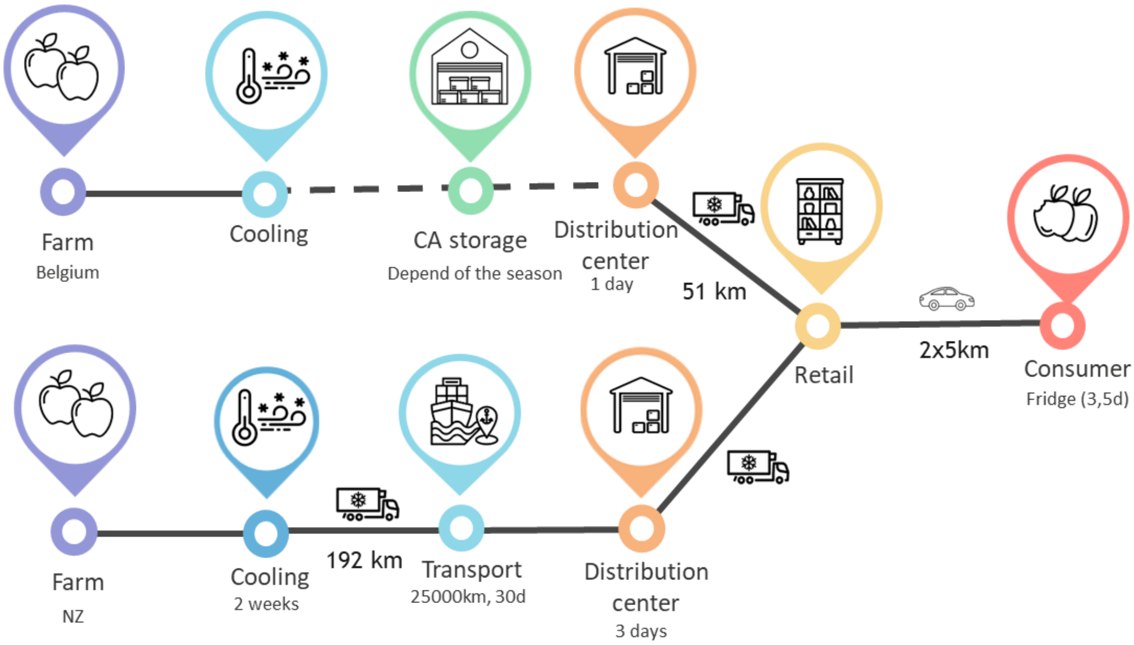


Figure 5: Apple supply chains from Belgium and New Zealand

New Zealand apples are shipped to Belgium by boat and there are two possible routes of different durations. 65% of the boats take a longer route of 33 days and over 29000 km, while 35% of the boats take a shorter route of 28 days and about 21000km. A distance of 26200km and a duration of 28,6 days are used for simulation.

The consumer travels to the store by car (a round trip of 2x5km). The maximum volume considered for consumer goods transport is 0.2 m^3.

Upon arrival at the consumer's home, it is assumed, based on the surveys, that the apples are stored in a domestic refrigerator for 3.5 days.

2.2.2 Switching from imported apples to local grown apples

The life cycle assessments (LCA) were performed by Goossens et al. using SimaPro 8 software and data from the Ecoinvent v3.2 database. Figure 5 compares the results of this assessment with the results of the simulation using the ENOUGH tool, considering a weighted average scenario based on apple sales shares. The results show that the evaluation of the global emissions is relatively similar. Differences occur mainly with the storage and the sea shipping stages for New Zealand apples.

For this case study, the major contribution is the transport stage, and particularly the transport by sea ship. Packaging also contributes significantly to emissions in this case study. Primary packaging include plastic bags and carboard trays, secondary packaging consists of carboard boxes and plastic trays, and tertiary packaging involves the use of wooden pallets (often with a thin plastic film). Emissions of tertiary packaging are often considered as negligible due to the reuse of the pallets.

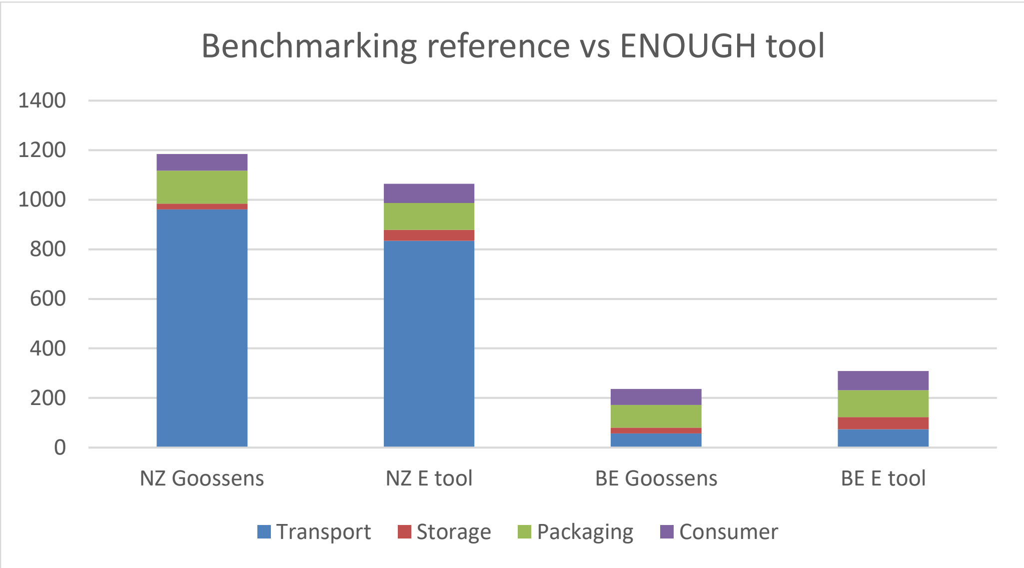


Figure 5 Comparison of emissions between reference and ENOUGH tool (average scenario)

Emissions vary depending on the month and on the duration of the storage stage in controlled atmosphere for BE apples or colds room for NZ apples. The highest emissions for BE apple occur in September just before the harvesting period, following 10 months of storage in controlled atmosphere. In the September scenario, it is particularly interesting to see if the emissions due to this storage stage exceed those from sea shipping of NZ apple.

Figure 6 show that, from an environmental perspective, a BE apple is always preferable to a NZ apple and this even in the worst-case scenario (September). Many studies [18–20] are in line with those results, concluding that even when taking into account long-term storage, domestic apples have a better environmental performance than those imported from the southern hemisphere (New Zealand, Chile, Brazil...).

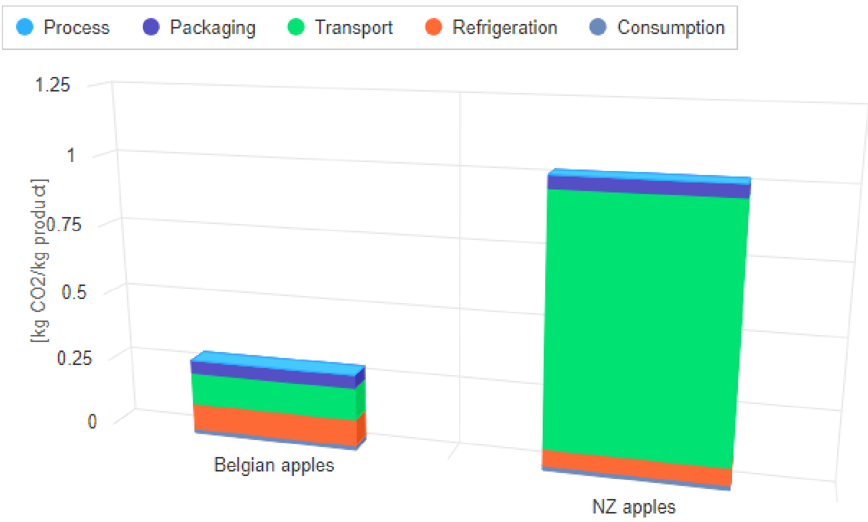


Figure 6: Comparison of emissions between BE apples and NZ apples in September

Even if the Belgian apple is available and sold throughout the year, the quality of BE apples after 10 months of storage in a modified atmosphere can be questioned and should be compared to the quality of NZ apple after 4 weeks of cold room storage. Two quality criteria are presented in Figure 7 and Figure 8. For both criteria, the quality of the local apple is higher than the quality of the imported apple.

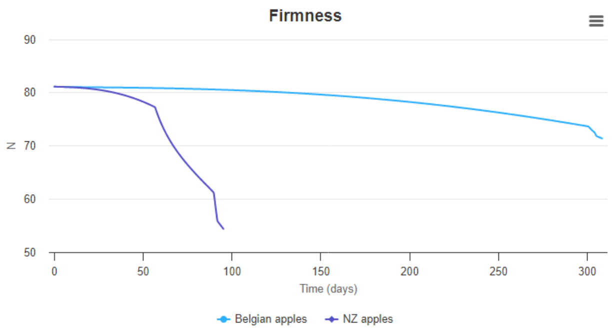


Figure 8: Firmness for BE and NZ apple in September

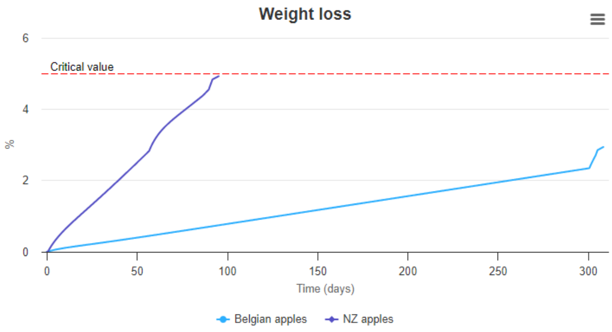


Figure 7: Weight loss for BE and NZ apple in September

Importing food products from locations like South hemisphere countries, when local grown products are also available, raises significant questions regarding environmental sustainability.

References and the simulations presented here consistently show that imported apples have a greater environmental impact than locally grown apples. This is mainly due to long-distance transportation which constitutes a significant portion of their carbon footprint.

2.2.3 Reducing emissions with low emission technologies and practices

To evaluate the potential of reduction for this case study, it is possible to simulate the use of the best technologies selected in WP2 roadmaps. For this case study, the most contributing stages are packaging, controlled atmosphere storage, the transport by truck and the transport by the consumer.

Packaging contribution is estimated from 50 to 100 g CO2 eq / kg of product, depending of the material used (cardboad trays, plastic bags as primary packaging and plastic crates, cardboard boxes as secondary packaging) and is a significative contributor to the total chain impact of NZ apples[16] due to the use of discarded cardboard boxes. Half of the BE apples is distributed in EPS boxes and half in carboard boxes. It is worth noting that EPS is 100% recyclable. We will assume here that Belgium can reach a high recycling rate in a close future. Switching for BE apples in carboard boxes to 100% recycled EPS boxes could then significantly reduce the total emissions of the supply chain.

BE apples sold in September have been stored in controlled atmosphere storage rooms during at least 10 months. WP2 technological road maps for food cold storage[21] identify 30 technologies and strategies that have a potential to reduce carbon emissions. Among these strategies, renewable energy (solar electricity) and floating condenser pressure have been chosen for the case study to reduce emissions of BE apple supply chains.

The emissions due to the 250 km transport by road can be also mitigated by following the recommendations of the WP2 road maps[22]. Concerning the refrigerated transport by truck, switching to a natural refrigerant (CO2) and using biomethane as fuel will be assumed in the simulation. The use of an electric car by the consumer instead of a diesel car is also considered.

Simulation results are presented in Figure 9 and summarized in

. Starting from the NZ supply chain with sea shipping transport to BE supply chain with retrofits, the reduction of emissions can reach until 89.9%.

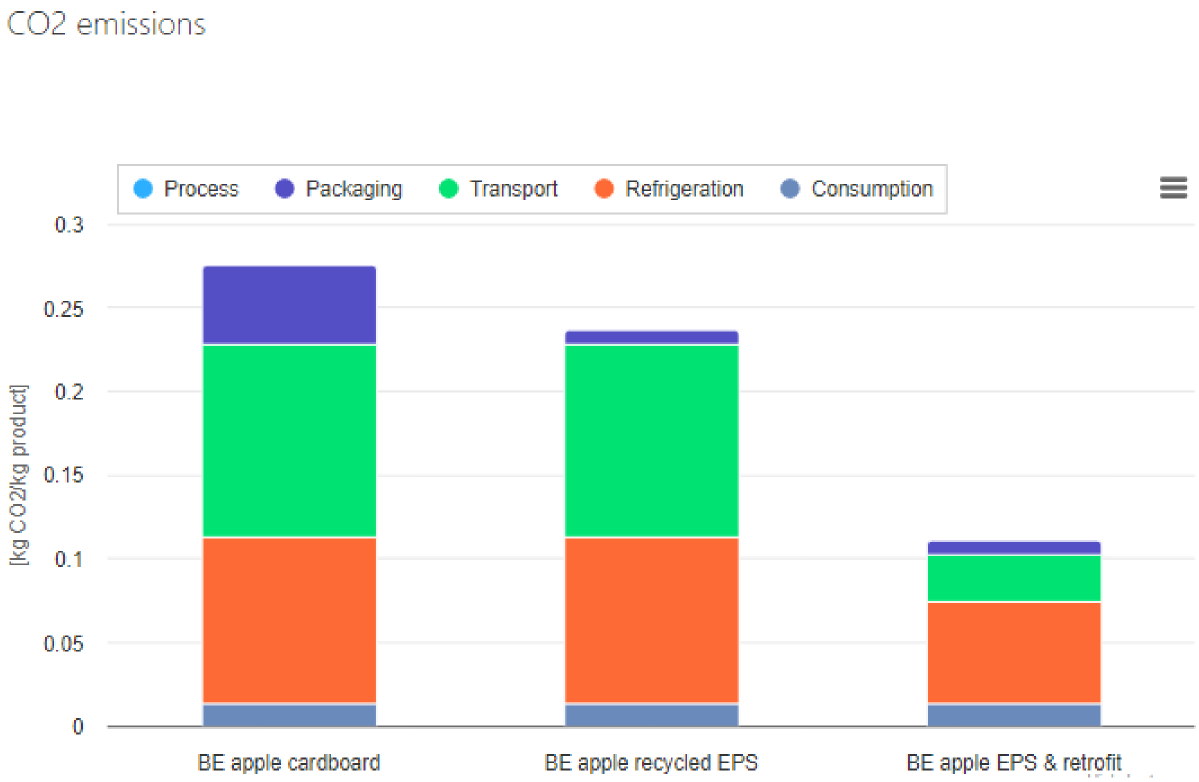


Figure 9: Mitigation of emissions using recycled packaging and implementing low emission technologies

Table 2: Overall emissions of apple supply chains and mitigation scenarios

Overall emissions				
Scenarios	NZ supply chain	BE supply chain	BE low emission packaging	BE low emission packaging & retrofits
g CO2 eq/ kg product	1014	275	237	111
Reduction (%)		-73%	-76.6%	-89.9%

Emission savings for the apple supply chain presented in this case study **can reach 90%** by switching to preferentially local grown products and using recycled packaging, floating condenser pressure and solar panels for cold storage, natural refrigerants and biomethane fuel for trucks, and electric cars.

2.3 The high carbon footprint of air transport

Emission intensity, typically measured in gCO2/ton.kilometer, represents the amount of CO2 emitted to transport 1 ton of goods over a distance of 1 km. This indicator is a key performance factor to consider to compare transport modes. Examples of emission intensities are given in [23]. For instance, transporting food by air emits around 50 times as much greenhouse gases as transporting the same amount by sea[23].

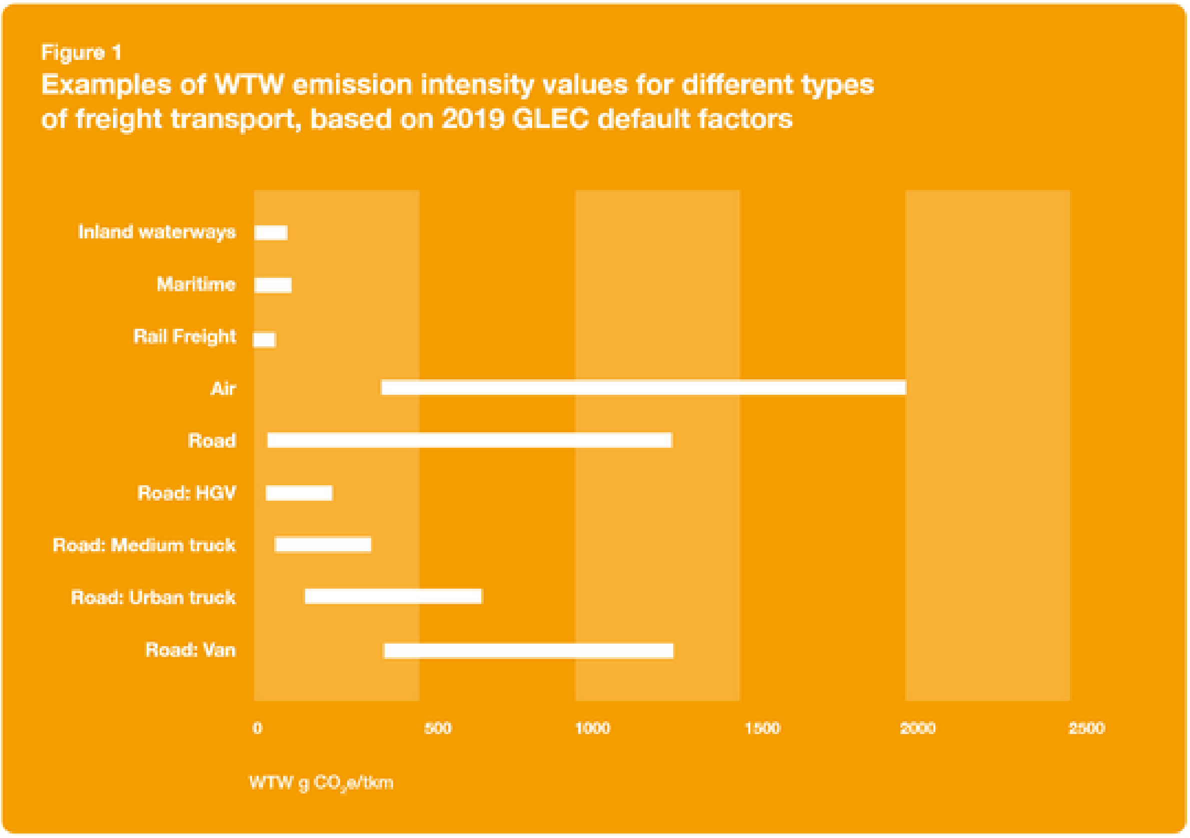


Figure 10: Examples of WTW (Well-To-Wheel) emission intensity values for different types of freight transport (source GLEC framework [23])

Air transport is the most emission-intensive mode of transportation and freight transport accounts for about 19% of total aviation-related emissions[23]. Nonetheless, aviation is anticipated to be one of the fastest-growing transportation sectors in the coming years, with a projected annual growth rate of approximately 3% through 2040.

Air freight transport is used for food products which are highly perishable. In this case, transport by boat is too slow. For instance, 10.8% of salmon exported from Norway in 2013 was transported out by air freight[24]. This modal share of transportation is mostly due a high demand coming from Asia in fresh product. In Japan, farmed Atlantic salmon from Norway and Chile is the top imported fish in the country[25]. Salmon, typically consumed in sashimi and sushi, is imported as a chilled product in expanded polystyrene boxes with ice and shipped by cargo (Figure 8), resulting in significant CO2 emissions.

Figure 11: Pallets of salmon ready for loading on to cargo aircraft (Photo from Andreas Witzoe[26])

Frozen Atlantic salmon transported by sea from Norway to Japan is an alternative solution. Even if distance can be estimated to around 26000 km Figure 12, emission intensity of maritime transport ranges from 3 to 90 gCO2/t.km when emission intensity from air transport ranges from 650 to 2000 gCO2/t.km, which compensates the larger distance.

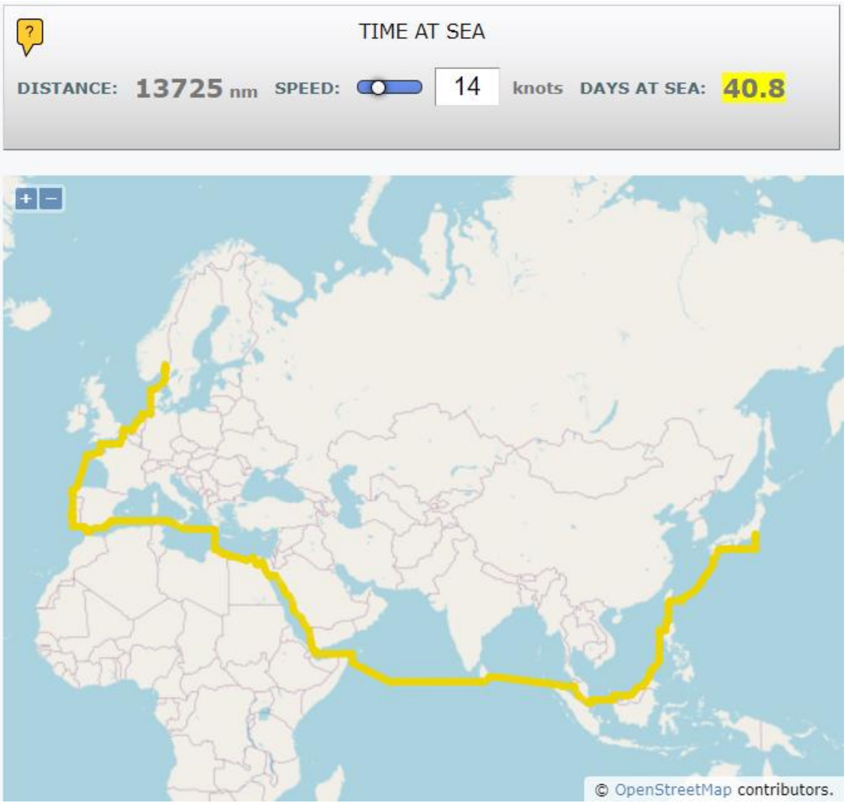


Figure 12: Distance and time at sea from Oslo to Tokyo seaport (http://ports.com/sea-route/port-of-oslo,norway/port-of-tokyo,japan/)

2.3.1 Case study description

The case study will start from the farm gate. It must be noted that chilled and frozen Atlantic salmons are farmed in the same way. The product is first going through a few processing activities, stunning, slaughtering, evisceration. These operations are similar for both chilled and frozen salmon. Freezing requires more energy than chilling. Chilled salmon is typically placed in expanded polystyrene boxes, with ice. These EPS boxes are 800 x 400 x 19 mm and 5 kg of ice is placed in a box with 20 kg of salmon. Frozen salmon is placed in a carboard box with similar dimensions than the EPS box, with 24 kg of salmon and no ice in this case.

Boxes are then transported to the seaport or airport by truck, the distance from the airport is 478 km and the distance from the seaport is 428 km.

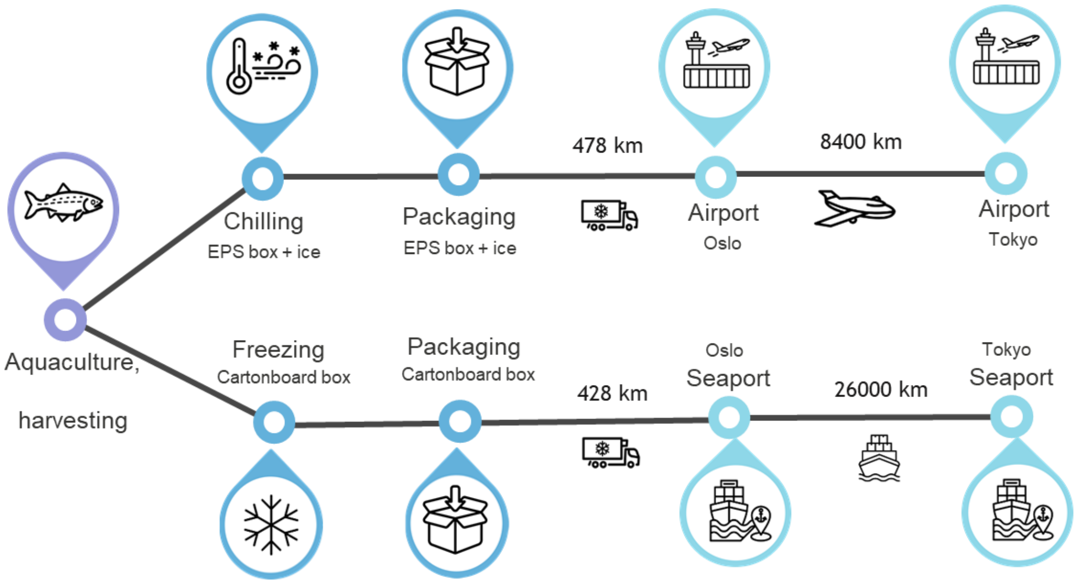


Figure 13: Chilled and frozen salmon supply chains for the case study

Distance for air shipping is 8407.2 km and duration is 1 day, when distance by sea (container ship) is estimated to 25407 km and 26 days.

2.3.2 Switching from chilled salmon transported by air to frozen salmon transported by sea

Chilled chain and frozen chain differ in this case by the processing and transport stages and the packaging. They are first transported by a heavy-duty truck. Redo et al. uses an emission intensity of 0.090 kg CO2eq/ton-km for this transport stage. The value for an articulated truck up to 34t used by the ENOUGH tool results in a very similar value of 0.094 kg CO2eq/ton.km. Emission intensity value for air freight used by Redo et al. is 0.519 kgCO2/ton-km. The value of 0.560 kgCO2/ton-km is recommended by the GLEC framework for a freighter and used by the ENOUGH tool. Emission intensities used for the container ship by Redo et al. and the ENOUGH tool are 0.0256 kgCO2/ton.km and 0.02 kg CO2 /ton.km respectively.

Figure 11 compare the emissions of the chilled chain estimated by the reference paper[25] and the ENOUGH tool and Figure 12 compare the emissions of the frozen chain. For both cases, transport is the main contributor to emissions, reaching even 98% for the chilled salmon.

Redo et al. also presented the results of a sensory panel evaluation to compare chilled salmon and frozen salmon. They mention that the 32 panellists selected for the evaluation did not perceive any significant difference in the glossiness, smell, texture, umami, and juiciness of chilled and frozen salmon. Figure 13 presents the evolution of the Total Volatile Basic Nitrogen calculated by the ENOUGH tool. TVB-N is commonly used as a freshness quality index for meat and fish. Values of TVBN of frozen salmon after 27 days shows TVBN values lower than the values of fresh salmon after 2.3 days, revealing a potential better quality for the product.

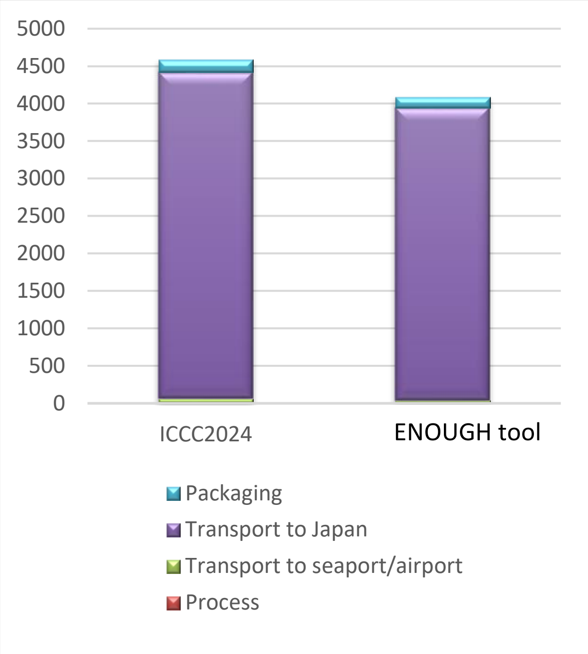


Figure 14 : Emissions for the chilled salmon

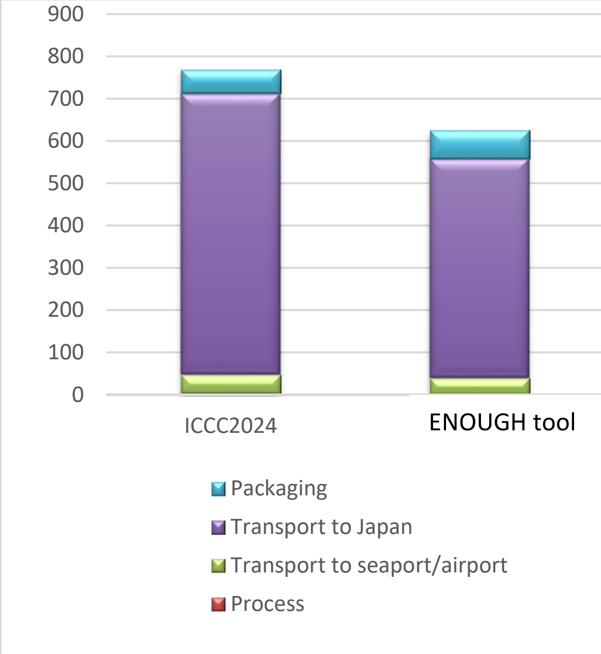


Figure 15: Emissions for the frozen salmon

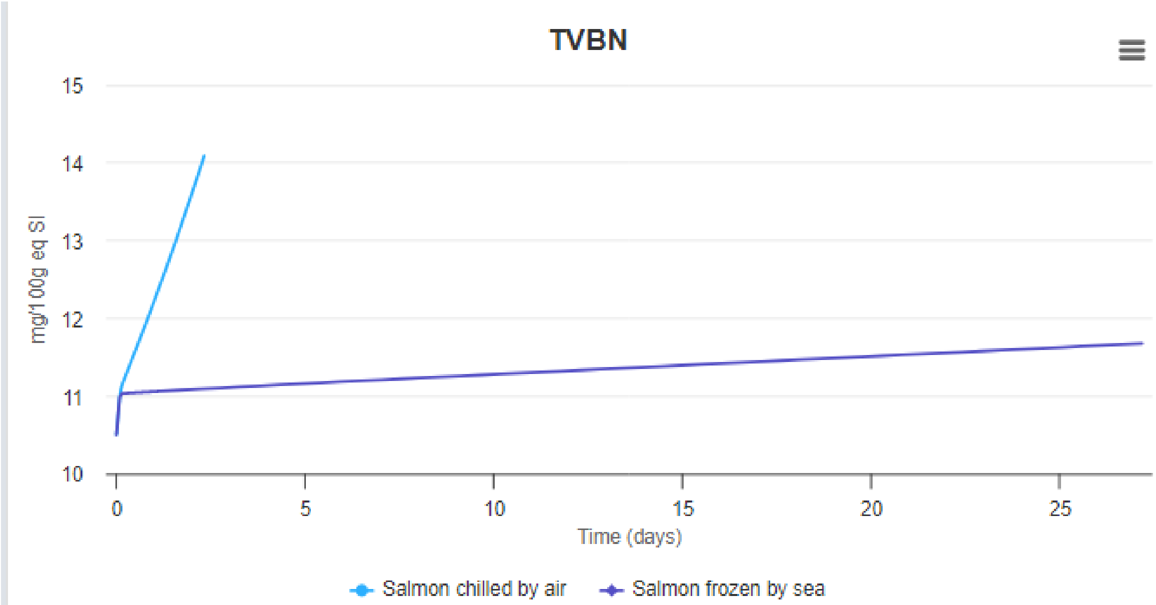


Figure 16: TVBN values for salmon and frozen chains

Switching from air transport to sea transport for this case study, even if it multiplies the distance by 3, **reduces the emission** due to this long-distance transport **by 90%**. The additional emissions for the frozen salmon due to the freezing process and the low temperature transport conditions appear in this case negligible compared to the emissions savings by switching from air to sea transport. This **alternative to chilled salmon** shows a good potential in terms of CO2 emission savings and quality criteria.

2.4 Last mile delivery: a critical step in supply chains carbon footprint

2.4.1 Introduction

Rizet et al.[27] used the yoghurt supply chain as one of four case studies to discuss the transport activities and their associated CO2 emissions. Yoghurt was selected here as a good example of a perishable product consumed in the country it was produced. Primary data used for calculation are detailed in the report by Rizet et al.[28]. Those data (type of vehicle, mass transported, distances, fuel used…) are based on an extensive review with data collected from organisations including manufacturers, retailers and transport companies.

Various scenarios with different “home deliveries” (from large superstores, supermarkets, and minimarkets versus an e-commerce chain) and with different loads transported, are used to benchmark this supply chain. Production, transport, retail and consumer stages are found to be all contributors to the emissions of this supply chain, with significant differences of the transport emissions due to the last mile delivery.

The “last mile delivery” is often reported in studies as a significant contributor to food supply chains emissions. This is mainly due to the use of personal vehicles and the small amount of products transported. The majority of consumers travel by car to hypermarkets and supermarkets, leading to significant energy consumption and CO2 emission by kg of product. In contrast, smaller neighbourhood stores benefit from a higher proportion walking, which considerably reduces the emissions. It must be noted than the use of eco-friendly alternatives such as electric vehicles is rarely mentioned in the studies and should also reduce significantly the emissions.

Compared to conventional deliveries by the consumer, e-commerce is also cited as a potential source of emission savings. Dedicated e-commerce logistics platforms, combined with optimized delivery routes, can transport and deliver goods with lower energy consumption and CO2 emissions per product than consumers traveling to hypermarkets or supermarkets. Unlike traditional commerce, e-commerce does not require physical stores, which are significant sources of energy consumption (heating, air conditioning, lighting…). However, it must be noted that this is highly dependent on several factors like the optimization of delivery routes, the mode of transport used and the consumer behaviour (grouping orders, choosing the delivery mode).

This case study focuses on the national yoghurt supply chain in France and compares different scenarios for the last delivery: hypermarket, local store and e-commerce, using the primary data from Rizet et al.[27]. Further emission reductions are also explored using technologies recommended in the WP2 roadmaps.

2.4.2 Case study description

The production stage of yogurt in factories includes pasteurization, fermentation, packaging and storage in cold rooms before shipping. It is usually then transported to a logistics platform and then to a distributors' platform. This transport stage is generally done by refrigerated semi-trailers capable of transporting a large volume. Finally, the yogurt is transported to the stores (hypermarkets, supermarkets, neighbourhood stores) by smaller refrigerated trucks, suitable for urban deliveries. The last link in the cold chain (Figure 17) is the consumer's trip from the store to their home. The distance, mode of transport and quantity of goods transported by the consumer influence significantly the overall energy efficiency of the cold chain.

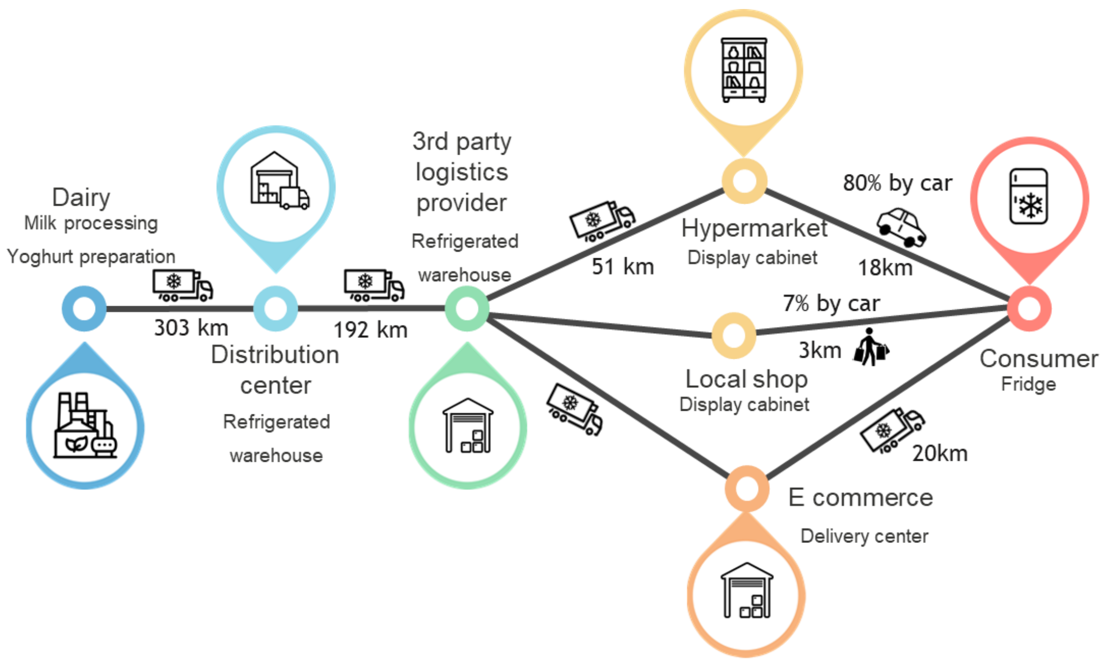


Figure 17: Yoghurt chain

2.4.3 Simulation results, benchmarking the tool

A comparison of emissions calculated by the ENOUGH tool and presented in the reference paper is presented in Figure 18 for the “hypermarket” scenario. The global values of emission are similar, around 250gCO2/kg of yogurt. The main difference come from the last mile delivery, where the amount transported directly influence the result. It can be noted from these results that the most contributing stages to the global emissions are production and transport stages, and in a smaller proportion, retail, but that packaging is not included in the global emissions since it was not taken into account in the reference paper.

Production requires a significant amount of energy, primarily for heating (pasteurization) and cooling. Heating is mostly provided by combustion of gas, emitting significant amounts of CO2. Energy source for cooling is mainly electricity, hence the CO2 emission depends on the country.

Yogurt is a perishable product and requires refrigeration, including during transport stages. The energy used for refrigeration in trucks is usually estimated at 15%[23,29,30]. The corresponding CO2 emissions depend on the energy source (fuel or electricity) of the refrigerating unit and of the duration of the trip (more than the distance), as the refrigerating system is still running when the truck is stopped.

The retail stage is known as being an energy intensive stage. Refrigeration of shelves, lighting, air conditioning and other electrical equipment used in a store contribute to a significant energy consumption. The size of the store influences energy consumption per kg of yogurt sold: the larger the store and the higher the sales volume per square meter, the lower the energy consumption per kg of yogurt sold.

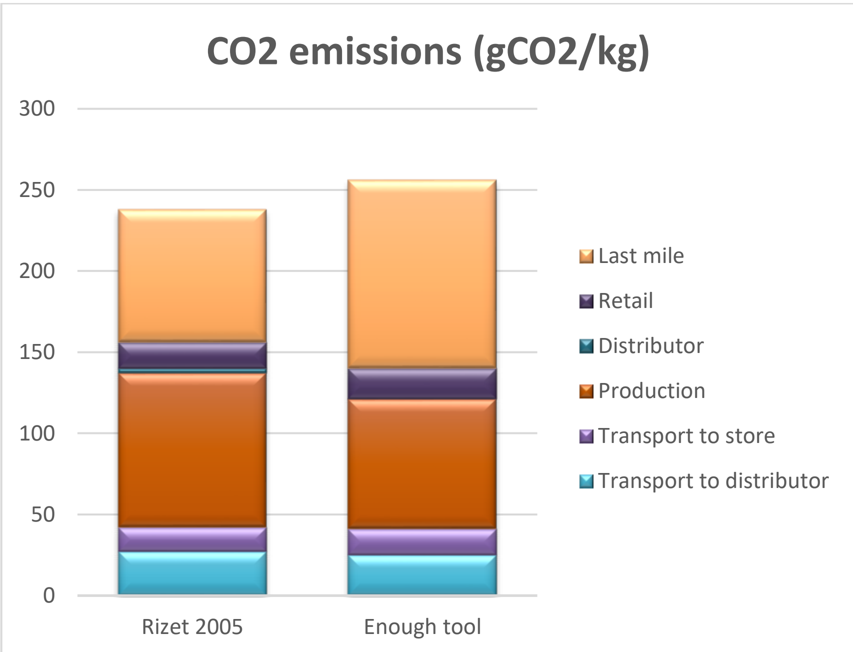


Figure 18: comparison between Rizet et al. results and ENOUGH tool

The following emissions presented will also include packaging (between 90 to 180 g of CO2 equivalent by kg of product[31]). By using plastics (often polypropylene) and around 7 g of packaging per 100g of product, these emissions represent a large share of the global emissions for the yogurt supply chain. We will focus in this case study on the transport stages.

Figure 19 presents the results for the selected last mile delivery scenarios:

- Hypermarket: 80% by car, 18 km trip
- Local store: 7% by car, 3 km trip
- E-commerce: delivery by truck, 20 km trip

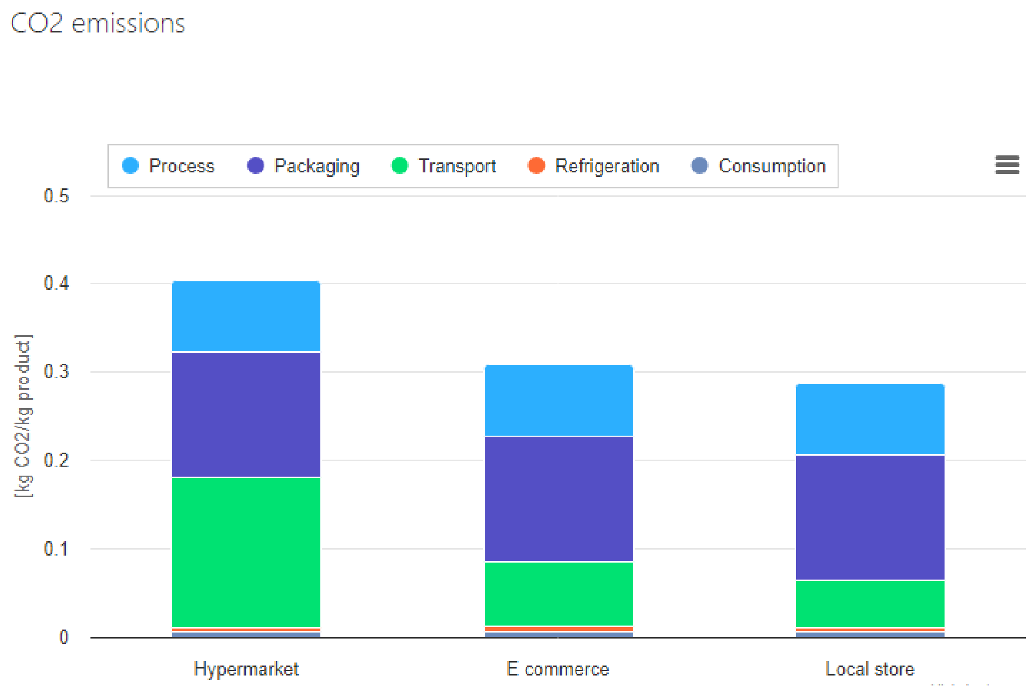


Figure 19: Comparison between different last mile delivery modes

Hypermarkets, despite economies of scale are less energy-efficient than small local shops when including the consumer's trip to the store. The average distance travelled by car to reach a hypermarket or a supermarket is significantly higher than for small local shops. The percentage of customers using cars in this case reach 80%, compared to the 7% for neighbourhood shops. The average weight of purchases is higher in the case of a hypermarket, but that doesn't compensate the difference of transport modes.

If we consider the logistics before reaching the consumer, e-commerce scenario appears more efficient in terms of CO2 emissions than the hypermarket scenario. This is mainly explained by the absence of physical stores. Dedicated e-commerce logistics platforms and home deliveries can be more efficient than traditional stores and individual consumer trips.

Local store scenario appears to have the lowest impact in terms of CO2 emissions for this case study. This is mainly due to the reduction of emissions related to consumer transport, small local shops are generally closer encouraging walking or cycling.

The **Last Mile delivery** to the consumer can be very energy intensive compared to other transport stages. This is mostly due to the low load factor of vehicles and the predominance of private cars. By eliminating the physical store, **e-commerce is an alternative with a 22% reduction** compared to the hypermarket scenario. **Small local shops** help to reduce the emission impact of the last mile even more (**27% in this case study**) by promoting soft modes of transport such as walking and cycling.

2.4.4 Reducing emissions with low emission technologies and practices

Switching to a natural refrigerant like ammonia or CO2 can reduce energy consumption and emissions. In the next scenario, R717 (ammonia) will be used in cold storage stages (distribution centre and logistics provider) and R744 (CO2) will be used in the refrigeration units of trucks.

Floating condensation pressure is a strategy to lower the discharge pressure, when refrigeration systems typically operate with a minimum condensing head pressure. Floating heat pressure can achieve energy and indirectly CO2 emission savings of 5 to 12%. Floating condensing pressure will be included in the next scenario.

Another technology suggested by the ENOUGH tool (from WP2 roadmaps) is the use of biomethane for transport. Biogas converted to biomethane through purification can be readily used in natural gas-powered vehicles as another option to fossil natural gas. Biomethane as a transport fuel provides a sustainable and readily available alternative for conventional transport fuels with a payback time from 3 to 12 years, and will be used in the next scenario.

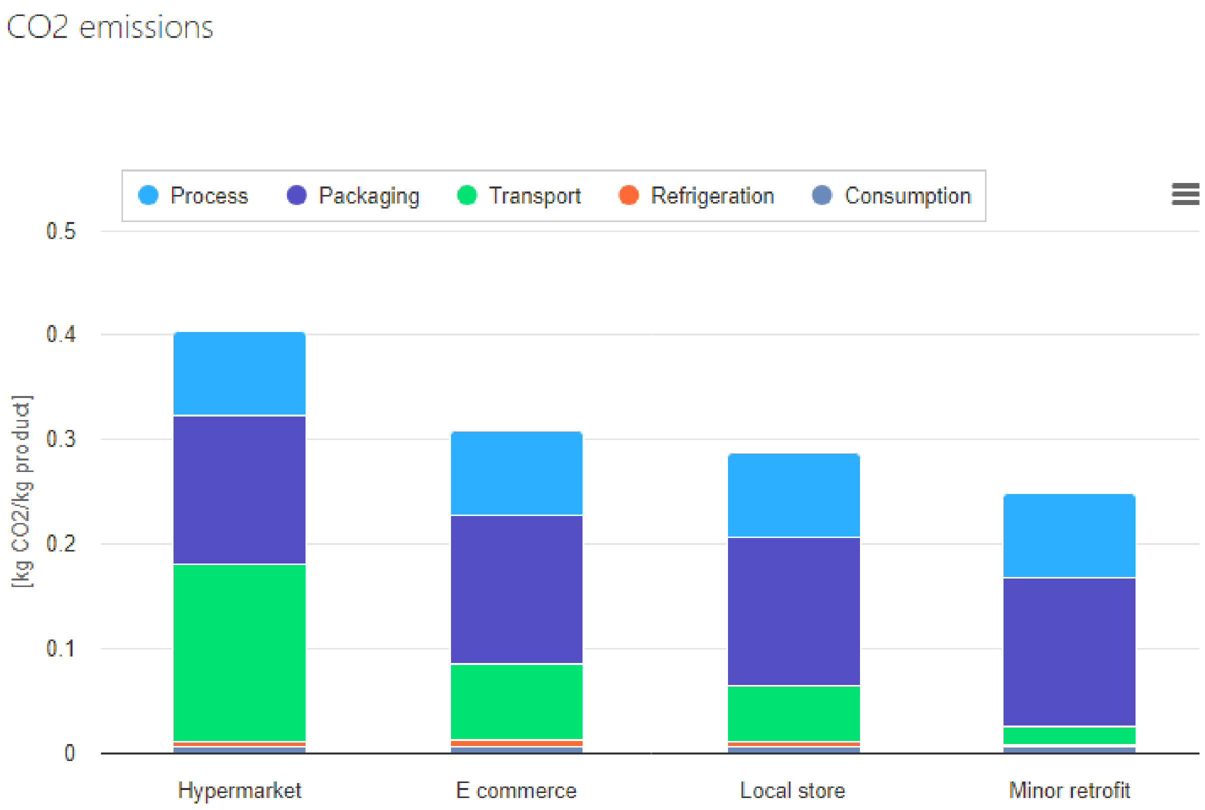


Figure 20: Potential emissions savings for yoghurt chain with retrofits

Figure 20 presents the CO2 emissions for the local store scenario with the previously cited retrofits ("minor retrofit" scenario): ammonia and CO2 refrigerants, floating condenser pressure and biomethane as fuel for trucks. With the systematic use of these technologies along the whole cold chain, additional emission savings to the local store scenario are estimated to 13.5%, most of it coming from the transport stage.

It must be noted that production and packaging represent a large proportion of the global emissions of the final supply chain. Alternatives to plastic exist, such as glass, carton board and biodegradable plastics[32]. Additional emission savings for the production are also possible.

For a supply chain like the yoghurt chain studied where **transport emissions are a major contributor**, and especially the home delivery stage, at least **38% emission savings can be reached** by switching to better logistic practices (e-commerce, local shops…) and a few low emission and available technologies (natural refrigerants, biomethane fuel, floating condenser pressure…). Even more savings could be reached by switching from plastic to low emissions materials for packaging, and reducing emissions from the production stage.

2.5 Benchmarking of frozen food cold chains based on temperatures 3˚C warmer than current norms

2.5.1 Introduction

Production and distribution of perishable foods in an energy efficient manner presents a challenge. To lower raw material temperatures and maintain them after or through multiple cold chain stages such as processing, storage, transport, retail and domestic refrigeration requires extensive energy-consuming equipment. Despite advances in equipment design and operation, it is of fundamental importance that chilled and frozen foods are stored at temperatures which offer all the advantages of extended food quality and safety, but which from an energy efficiency viewpoint are not colder than needed. Maintaining nutritional values and avoiding food waste can thus be achieved without excessive environmental penalties and energy costs.

Currently frozen food cold chains are typically operated at an often legally defined temperature of -18°C, a temperature considered suitable for the widest range of products, offering vast extensions in storage life compared with chilled temperatures. However, for many of these products the need for temperatures as low as -18°C is questionable. This temperature was introduced many years ago when attention was focussed more on safe margins of operation for less effective equipment, and it is apparent that for at least some products it may be possible to achieve acceptable retention of quality and safety at warmer temperatures. This is particularly evident for safety, where microbiological activity ceases at temperatures below -12°C and there is no need for -18°C. Maintenance of quality however, in terms of retention of nutritional value, slowing the development of rancidity for meats and impacts on other traits is more sensitive to temperature rises, and in most cases it is unlikely that temperatures could be raised as high as -12°C.

There is already some support in the frozen foods industry for the concept of warmer cold chain temperatures. For example industry-led studies[33,34] have estimated the savings that could be achieved by raising frozen storage temperatures from -18°C to -15°C (British Frozen Food Federation 2009) (Nomad Foods 2023)**.** These studies estimated energy savings of approximately 10% but were limited to only the storage blocks in the chains. In practice however, changing cold chain temperatures results in impacts on almost all the blocks in the chains, not just storage. The modelling described in this case study therefore extends the scope of temperature rises to all appropriate blocks in the frozen food cold chains. In doing so it aims to assess the reduced energy consumption and emissions benefits of raising temperatures for -18°C to either -15°C or -12°C, and whether either change could be achieved without unacceptable trade-offs in quality for a range of food types.

2.5.2 Case study description

Reference cold chains developed during the Horizon 2020 EU FRISBEE project were selected as the baselines for three frozen products included in the ENOUGH cold chain modelling tool[35] – ground beef, spinach and apple. While these may not be the ideal representative products or cold chains, they were extensively developed and tested in previous FRISBEE research and validated against examples from industrial applications.

For the chains, the temperature settings and durations of each block were used as input in the ENOUGH tool. They were then adjusted such that -18°C blocks were changed first to -15°C blocks and then to -12°C blocks, with the tool predicting energy consumption, emissions and impact on various quality traits.

The chains were as follows:

- Frozen ground beef (mince)

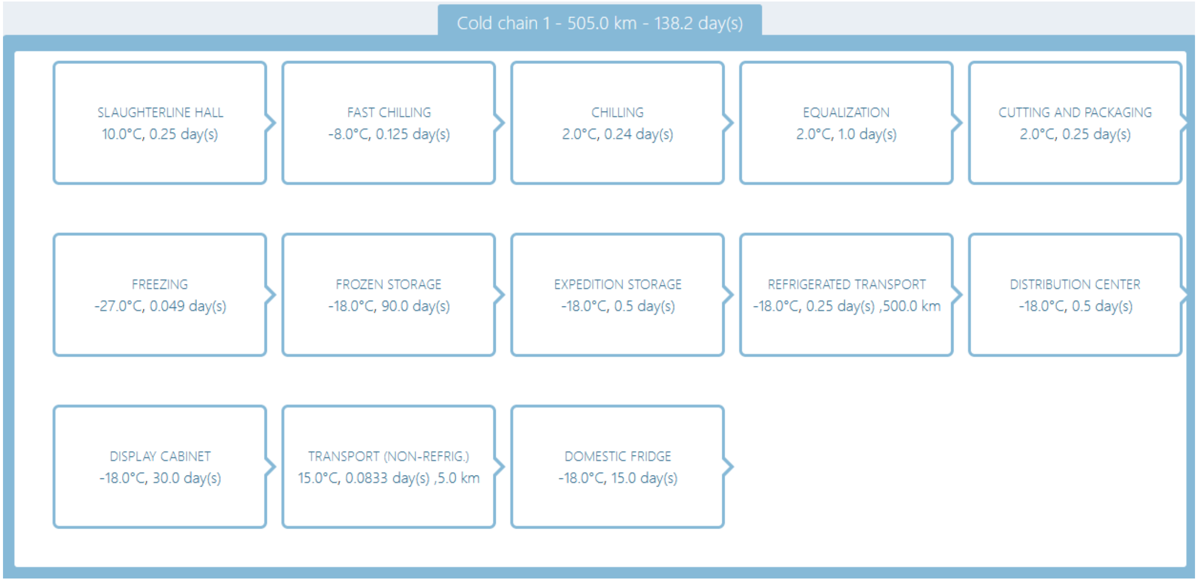


Figure 21: Frozen ground beef chain

- Frozen spinach

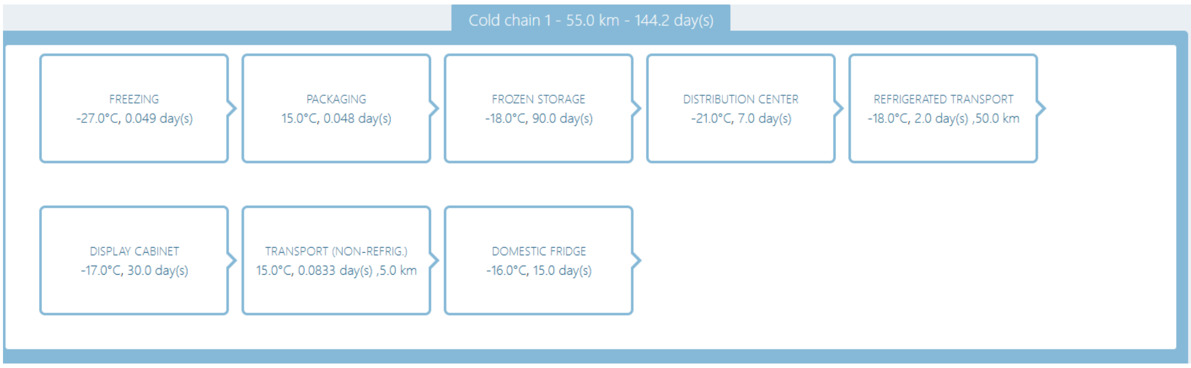


Figure 22: Frozen spinach chain

- Frozen apple

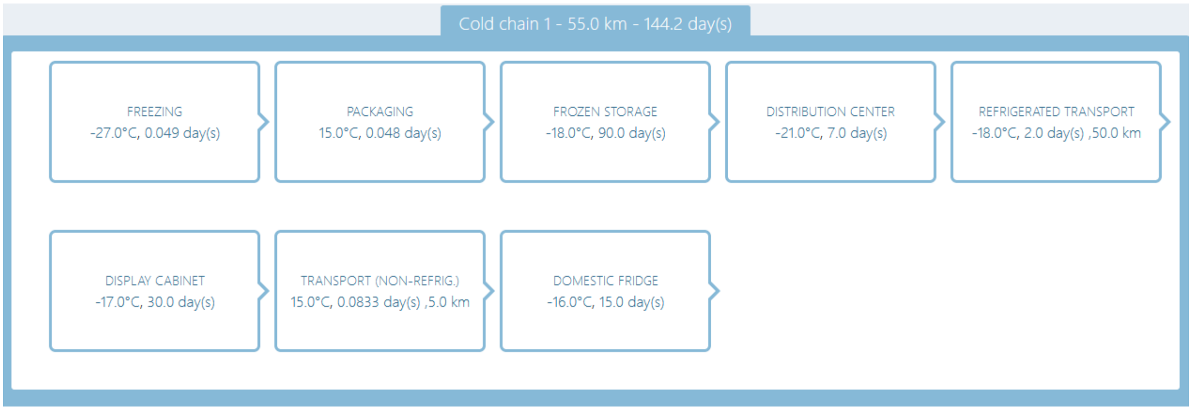


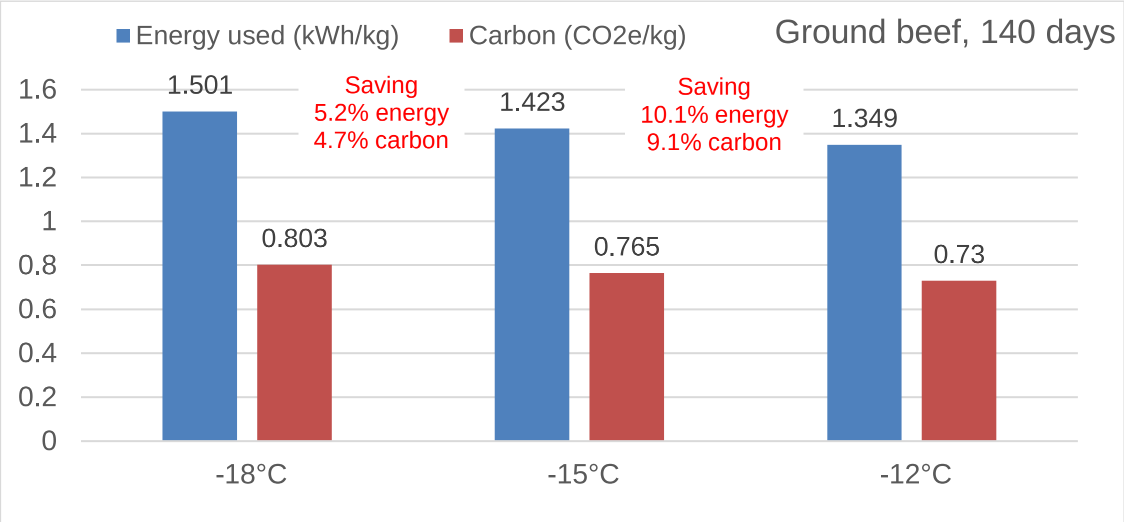
Figure 23: Frozen apple chain

2.5.3 Simulation results

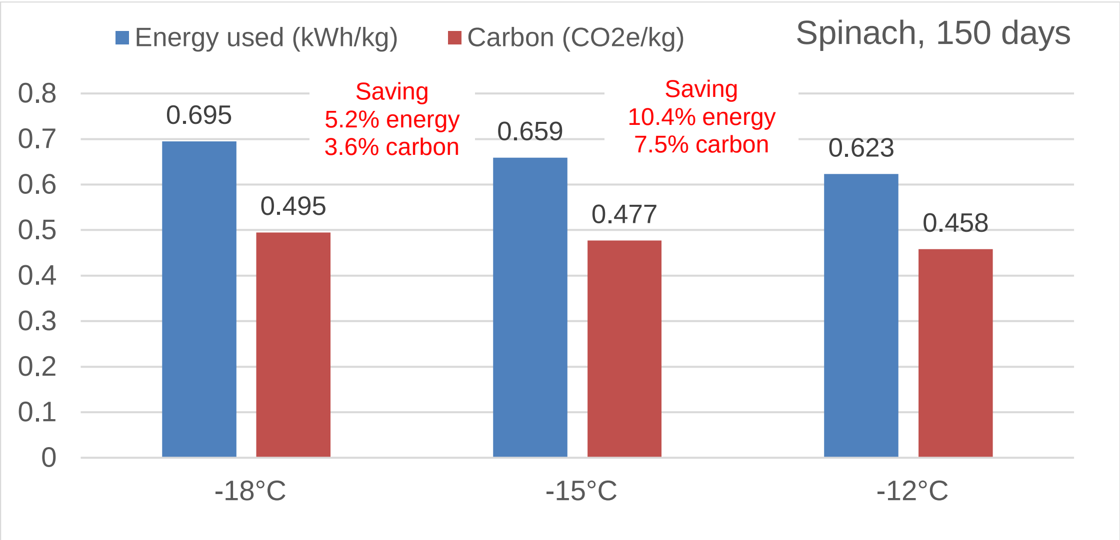
2.5.3.1 Energy consumption

For each of the product cold chains modelled, raising the frozen set point temperatures from -18°C to -15°C and then to -12°C had the anticipated effect of saving energy and reducing emissions.

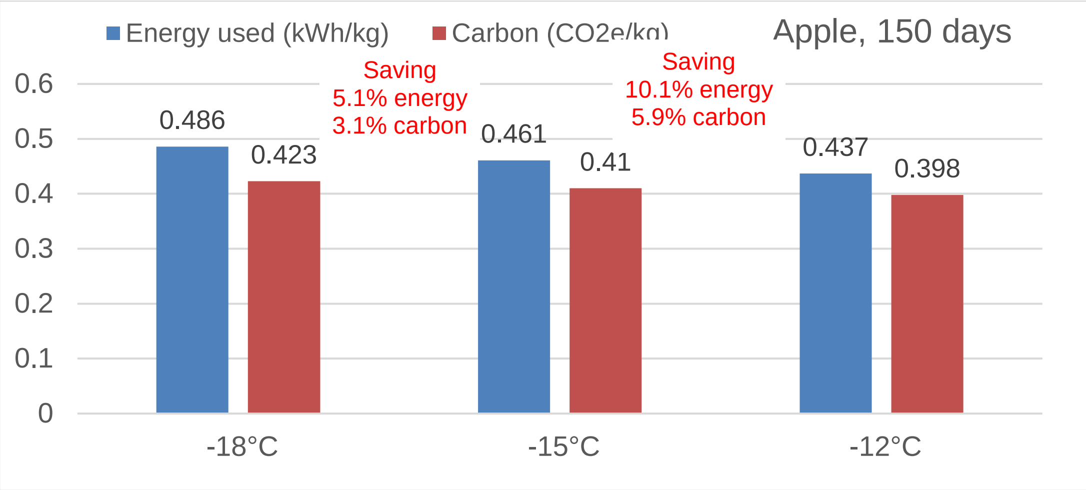
- Ground beef



- Spinach



- Apple

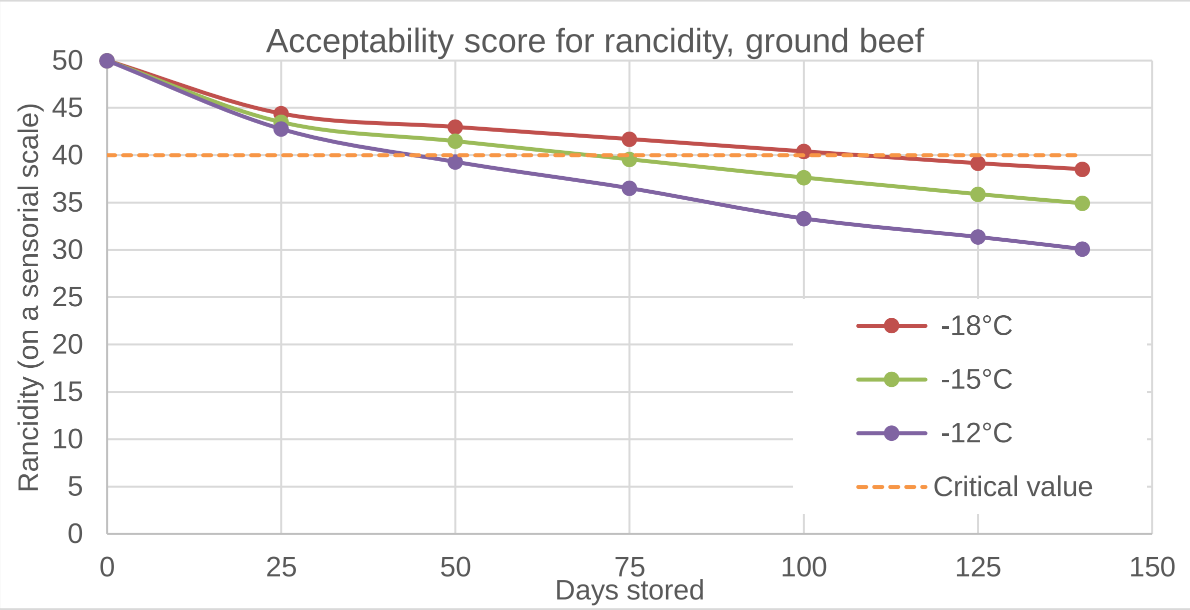


On average, raising the -18°C blocks in the chains to -15°C reduced energy consumption by 5.2% and emissions by 3.8%. Raising the blocks to -12°C reduced energy consumption by 10.2% and emissions by 7.5% compared with their original -18°C values. The difference in percentage reductions between energy and emissions is due to the different energy sources - for example transport blocks using diesel as the fuel have a different impact on emissions compared with electrically driven cold storage blocks.

2.5.3.2 Quality traits and shelf-lives

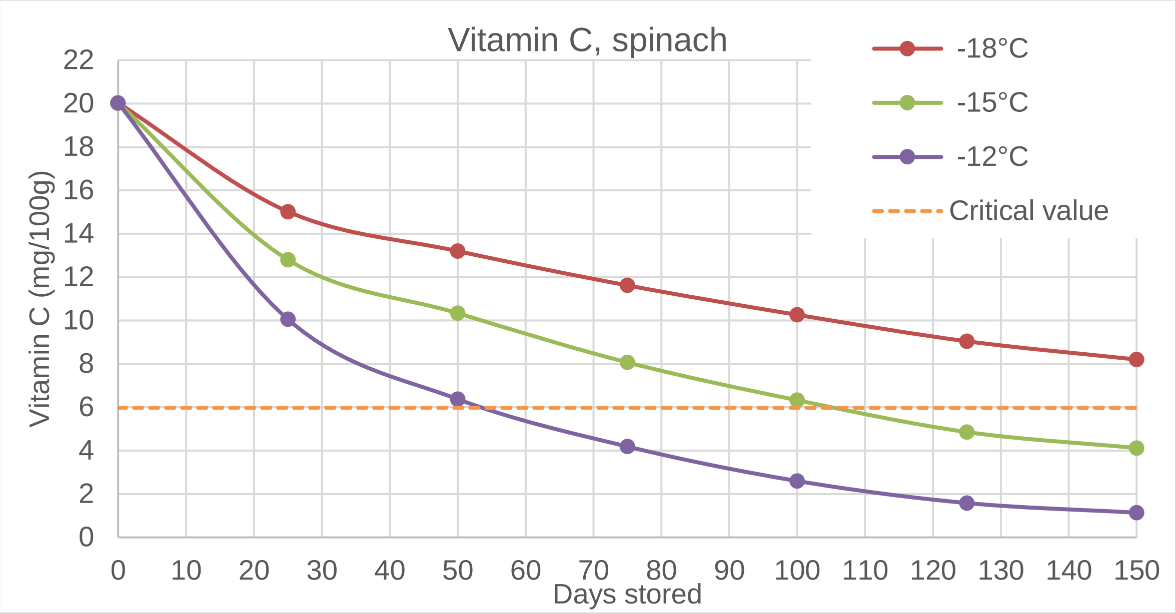
Raising the frozen cold chain block temperatures also had the expected impact on quality traits for the various food types.

- Ground beef – acceptability of rancidity based on a sensorial scale (see ENOUGH tool for details)



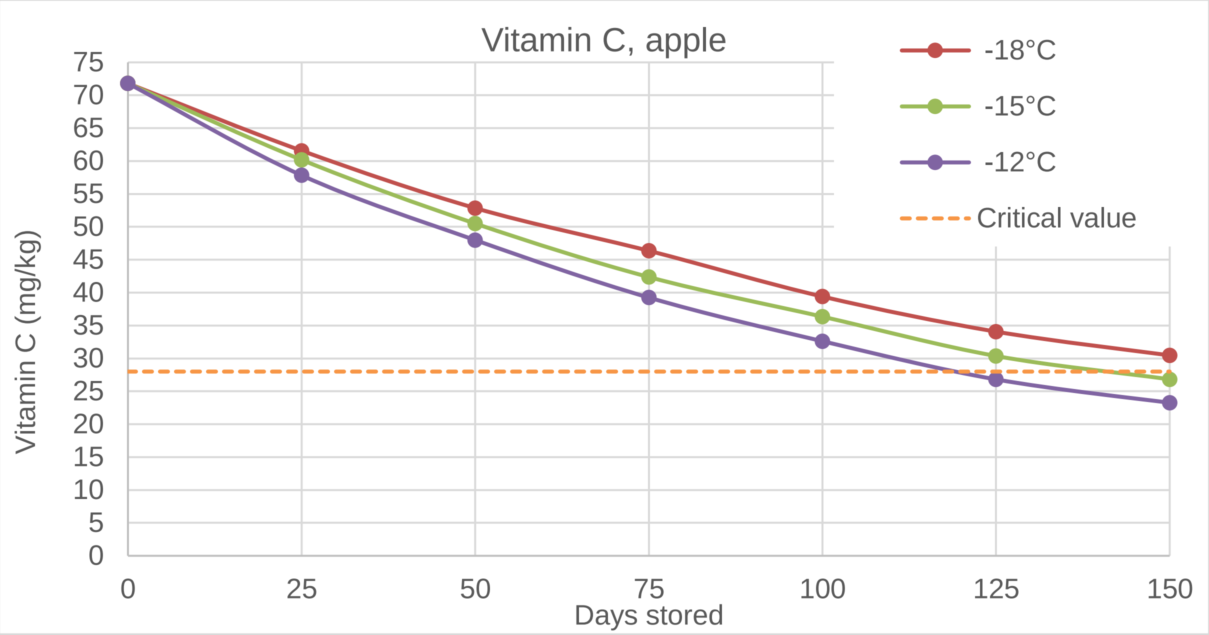
For beef in the -18°C cold chain, rancidity was acceptable up to approximately 110 days. This reduced to around 70 days for the -15°C chain and around 40 days for the -12°C chain.

- Spinach – vitamin C content



For spinach in the -18°C cold chain, vitamin C retention was acceptable for up to 208 days. This reduced to around 105 days for the -15°C chain and around 54 days for the -12°C chain.

- Apple – vitamin C content



For apple in the -18°C cold chain, vitamin C retention was acceptable for up to 160 days. This reduced to around 140 days for the -15°C chain and around 120 days for the -12°C chain.

Reductions in energy consumption and emissions for the warmer frozen cold chains were, as would be expected, achievable and useful for all product types. Emission savings ranged from 3.1% to 4.7% at -15°C and from 5.1% to 9.1% at -12°C. However, the **impacts on quality traits** varied with product type, with ground beef and spinach having significant reductions in quality in the -15°C chain, and what would perhaps be prohibitive reductions in the -12°C chain. Apple was less impacted but was still adversely affected.

From these results, raising frozen cold chain temperatures from -18°C to -15°C might be acceptable if some reduction in storage life is planned for. On the other hand, raising temperatures to -12°C may be a step too far, as reductions in quality retention were considerable. Vitamin C retention in spinach was the most extreme example of this, reducing from 208 days at -18C to 105 days at -15C and only 54 days at -12C.

2.6 Salmon supply chain in Norway

2.6.1 Introduction

Norway is one of the largest salmon producers in the world [36]. The farmed salmon chain is complex, including feed production (imported ingredients), salmon production (juvenile production and grow-out phase), slaughter, post-harvest processing and transport to market [37]. The majority of produced salmon in Norway is exported, and the exports are dominated by fresh whole salmon (head on gutted, HOG) to Europe (70%), followed by fresh whole to Asia (11%) and fresh fillets to Europe (5%)[38]. A small fraction is being sold as frozen.

In 2020, SINTEF published a report analysing greenhouse gas (GHG) emissions from different Norwegian seafood products [39], including a selection of salmon products dominating the statistics exported to typical destinations. In the ENOUGH project, the ENOUGH tool[35] is under development to estimate GHG emissions along the food chain and to help to identify bottlenecks where improvements to the food chain can be applied. Additionally, the ENOUGH tool incorporates product quality as an assessment parameter.

The aim of this work was to perform a benchmarking activity, establishing a comparison of the ENOUGH tool to the SINTEF report to potentially indicate the benefits and shortcomings of the tool. This was done by investigating and comparing a specific salmon cold chain from the SINTEF report to the ENOUGH tool. The cold chain steps that are included in this work are processing, transport and packaging. The outcome is given in this report as a short evaluation of the tool and suggestions for further upgrades.

2.6.2 Case study and cold chain description

A specific cold chain was chosen from the SINTEF report by Winther et al. [39] for comparison to the ENOUGH tool. As stated in the introduction, a majority of salmon is exported to Europe [38], and therefore, a salmon cold chain to Europe was chosen. The report by Winther et al. [39] describes several salmon cold chains where salmon is being transported to Europe, which vary by means of transport, fresh or frozen salmon and byproduct utilization in market (BUiM). Since the byproduct utilization in market is not part of the ENOUGH tool, a cold chain with low byproduct utilization in market was chosen (BUiM 30%).

The chosen salmon cold chain simulated in the current case study was fresh salmon fillets (B-trim), transported to Paris by road and ferry. The salmon was packaged in an EPS box with ice. Table 3 shows detailed information of the salmon cold chain.

Table 3: Detailed information of the simulated cold chain, based on Winther et al. [39]

Specie	Product	Packaging	Transport from	Transport to	Transport type	Transport type 2
Salmon	Fresh fillet (B-trim)	EPS box with ice	Norway	Paris	Road (2642 km)	Sea ferry (95 km)

2.6.2.1.1 Method

Cold chain data for the chosen salmon cold chain was obtained using the report by Winther et al. [39]. This data was used to simulate the cold chain using the ENOUGH tool as similar as possible to the chain from the report. Where data needed to simulate the chain in the ENOUGH tool was lacking from the report, assumptions were made as described in chapter 2.6.4.1.

The simulations were done in several rounds, with meetings with the developer of the ENOUGH tool between the simulations to clarify details. The deliverable D4.1[1] from the FRISBEE project was used to gain background information of the data and assumptions behind the tool.

Ultimately, the final cold chain was simulated and the results in terms of kg_{CO2e} / $kg_{product}$ presented and compared to the results by Winther et al. [39].

2.6.3 ENOUGH tool

The ENOUGH tool, which originates from the FRISBEE project, is a tool to determine the energy and greenhouse gas (GHG) emissions of different steps in the supply chain of food products. The product temperature is determined dynamically, and energy and GHG emissions are modelled as described in *"D4.1 Food supply assessment tool including renewable energy sources"*[1] and in *"An innovative tool to evaluate and optimize GHG emissions in the food supply"* [40]. The user can build an individual cold chain, ranging from the processing step to the domestic fridge. Each cold chain step requires inputs and parameters to determine the energy consumption and GHG emissions per step. Thereby, different cold chains can be compared easily, and the variety of products that are implemented provides many opportunities for the food industry. Besides evaluating the GHG emissions per kg of product the ENOUGH tool also provides the possibility to evaluate selected quality parameters of the product based on time-temperature correlations. The ENOUGH tool is updated continuously within the ENOUGH project, with new food types, quality parameters and other features being added.

2.6.4 Origin of the compared data

The aim of the report by Winther et al. [39] used in the current benchmarking activity was to quantify GHG emissions of the most important Norwegian seafood export products (including aquaculture) delivered to their typical markets. Based on volume and value of Norwegian seafood export, the authors defined some important chains varying the factors species, product form (whole fish, different trims of filets, etc.), processing, transport mode and market destination.

Data used in the report was mainly from 2017, collected using a "top-down" approach focusing on available data and statistics. If data was not found, data from individual companies was used, and interviews with industry and literature was used to validate assumptions/data.

For impact assessment of GHG emissions, the 2013 version of the IPCC impact indicators was used. The model was built in the LCA software SimaPro Developer MultiUser using background data drawn from ecoinvent for transports, energy production, fuels, materials, chemicals and infrastructure. Data drawn from the database Network for Transport Measures (NTM) for ferry transports.

The report included all steps from production to market for several species both within fisheries and aquaculture. For the purpose of comparing the report results and assumptions with the ENOUGH tool, only the three last steps (processing, packaging and export) were evaluated in this deliverable.

2.6.4.1 Assumptions and inputs

The following section presents the set inputs and parameters to the ENOUGH tool for the specified cold chain from Norway to Paris.

[1] https://enough-emissions.eu/download/65173/?tmstv=1707902032 (last accessed 14/02/2024)

Initial Condition

The tool requires an initial product temperature to determine the product quality dynamically. Currently, the processed fish is stored on ice and leaves the factory at approx. 4 °C. Hence, the initial product temperature is set to 4 °C.

Processing

Processing is modelled in the ENOUGH tool within the block “Processing and Packaging”. This step simulates the “processing and packaging” step as a cold store process, which calculates GHG emissions based on energy consumption of the refrigeration system to maintain a certain air temperature within the production facility.

In the current situation, fresh salmon arrives at the factory and is pre-cooled from approximately sea water temperature to 8 °C. Afterwards, salmon is chilled through RSW chilling and bled out. Subsequently, processing and packaging takes place, where fresh salmon is stored on ice.

Since the actual processing step differs majorly of what is currently implemented in the tool, it was decided to exclude the emissions from processing from the current work and to provide suggestions for further work for the processing step instead.

Packaging

The tool differentiates between primary, secondary and tertiary packaging, and requires information thereof to quantify the GHG emissions related to packaging. The report by Winther et al. [39] specifies secondary packaging by means of EPS boxes with an approximated thickness of 25 mm [41]. Tertiary packaging is assumed to be EPS boxes wrapped together by thin plastic foil on palettes. It was assumed that the plastic foil has a thickness of 0.01m.

Transport

Transportation is present in the chosen cold chain by truck and ferry transport. The required inputs, the chosen values and their source are presented in Table 4 for transport by road and in Table 5 for transport by boat.

Table 4: Inputs to road transport block in the ENOUGH tool

	Value	Unit	Based on source
Transport			
Vehicle category	road - articulated truck 40 t		[39]
Fuel type	Diesel		[39]
Distance (km)	2642	km	[39]

Duration (days)	5.871	d	[39] (where an average speed of 50 km/h, with 9h driving time per day is assumed)
Packaging			
Type of packaging	Tertiary		[39]
Room			
Room air T	0	°C	[42], [43], [44]
Room air humidity	50	%	
Heat transfer coefficient	9	W/m-K	[45]
Outdoor temperature	13	°C	[46]
Heat loads	Heat loads in terms of door openings per day are assumed to be 0.		
Additional loads	Additional loads are assumed to be 0.		
Evaporator			
$\Delta T_{1,evap}$	8	K	[47]
Fan / pump power	40	W/kW	[47]
Refrigerant	R452A		[39] The tool does not include the option of R452A, therefore R404A is chosen as a refrigerant.
is_eff	37	%	[48]
$\Delta T_{1,cond}$	10	K	[47]
Fan / pump power	60	W/kW	[47]
refrigerant charge	1.52	kg/kW	[39]
refrigerant leakage	10	%	[39]

Table 5: Input to boat transport in the ENOUGH tool

	Value	Unit	Based on source
Transport			
Vehicle category	Sea – Ro-Ro fleet average		[39]
Fuel type	Heavy Fuel oil		[39]
Distance (km)	95	km	[39]
Duration (days)	3.2	h	
Packaging			
Type of packaging	Tertiary		[39]
Room			
Room air T	0	°C	[42], [43], [44]
Room air humidity	50	%	
Heat transfer coefficient	9	W/m-K	[45]
Outdoor temperature	13	°C	[46]
Heat loads	Heat loads in terms of door opening per day are assumed to be 0.		
Additional loads	Additional loads are assumed to be 0.		
Evaporator			
$\Delta T_{1,evap}$	8	K	[47]
Fan / pump power	40	W/kW	[47]
Refrigerant	R452A		[39] The tool does not include the option of R452A, therefore R404A is chosen as a refrigerant.
$\eta_{eff,is}$	37	%	[48]
$\Delta T_{1,cond}$	10	K	[47]
Fan / pump power	60	W/kW	[47]
refrigerant charge	1.52	kg/kW	[39]
refrigerant leakage	10	%	[39]

2.6.5 Results and discussion: Comparison of a salmon cold chain between the ENOUGH tool and the SINTEF report in the categories of export and packaging

The inputs and parameters from chapter 2.6.4.1 were entered into the ENOUGH tool and the results in terms of kg_{CO2e} / $kg_{product}$ are presented below. The report by Winther et al. [39] provides only information on export, not transport and refrigeration individually, as the ENOUGH tool does. Therefore, the emissions from transport and refrigeration are summed together for results from the ENOUGH tool to compare it to Winther et al. [39].

It should be noted that the values from the report by Winther et al. [39] are estimated based on the available graphs in the report and thereby do include a certain level of uncertainty. For comparison purposes in this work, the order of magnitude is regarded as correct, and a qualitative comparison is given.

As visible in Figure 24, the ENOUGH tool simulation estimated the GHG emissions per kg of product lower than what is reported by Winther et al. [39] for both categories. The relative deviation is larger for packaging than for export.

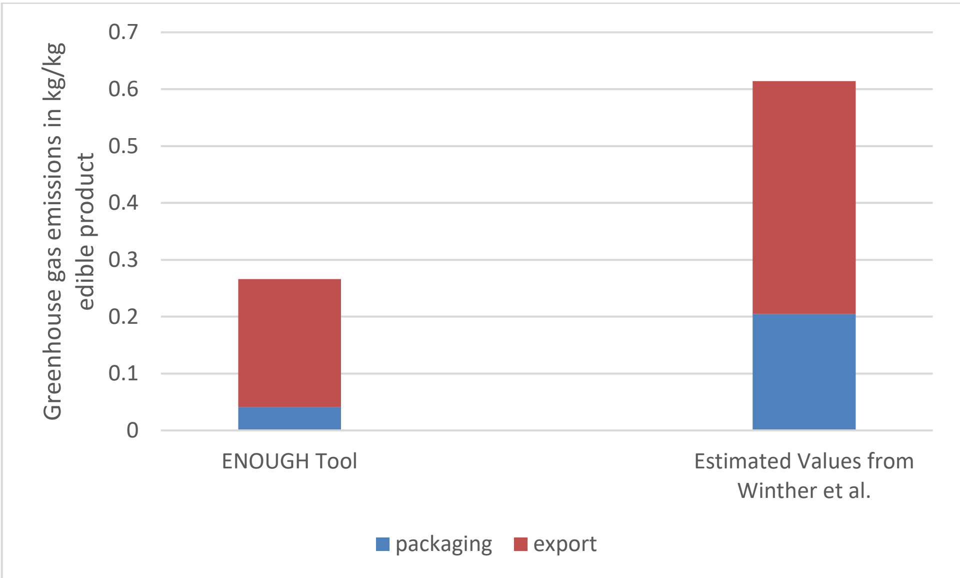


Figure 24: Comparison of GHG emissions from the chosen salmon cold chain (packaging and export, excluding processing) estimated using the ENOUGH tool and estimated values from the report by Winther et al. [39] . Values for the report by Winther et al. [39] are estimated and include uncertainties.

Within the simulation by the ENOUGH tool, GHG emissions related to refrigeration account for 2.6 % of the overall GHG emissions. Therefore, the major emissions related to export are due to transportation. Within transportation, the use of fossil fuel for propulsion is responsible for the majority of emissions, and the difference between the ENOUGH tool and Winther et al. can be likely explained by different factors calculating GHG emissions per t.km. Further investigation is required to which extent the choice of R404A instead of R452A does impact energy efficiency and GHG emissions.

Figure 25 shows the simulated surface temperature of salmon along the chosen cold chain. As one can see, the surface temperature decreases linearly to 3.87 °C at the end of transportation, since the truck trailer set-point temperature is set to 0 °C. However, salmon is usually stored on ice for truck transportation, and the surface temperature is expected to decrease much faster as the salmon is in direct contact with the ice. This showcases that salmon within the truck is treated as a cold store process and excludes the influence of ice on the product quality. Furthermore, the ENOUGH tool does not take product heat load into account during transportation, but only heat loads due to heat ingress and internal heat loads (lighting and door openings). For the next development stage of the ENOUGH tool for salmon cold chains, the tool should be updated to include the effect of cooling salmon on ice to correctly evaluate the decrease in product quality.

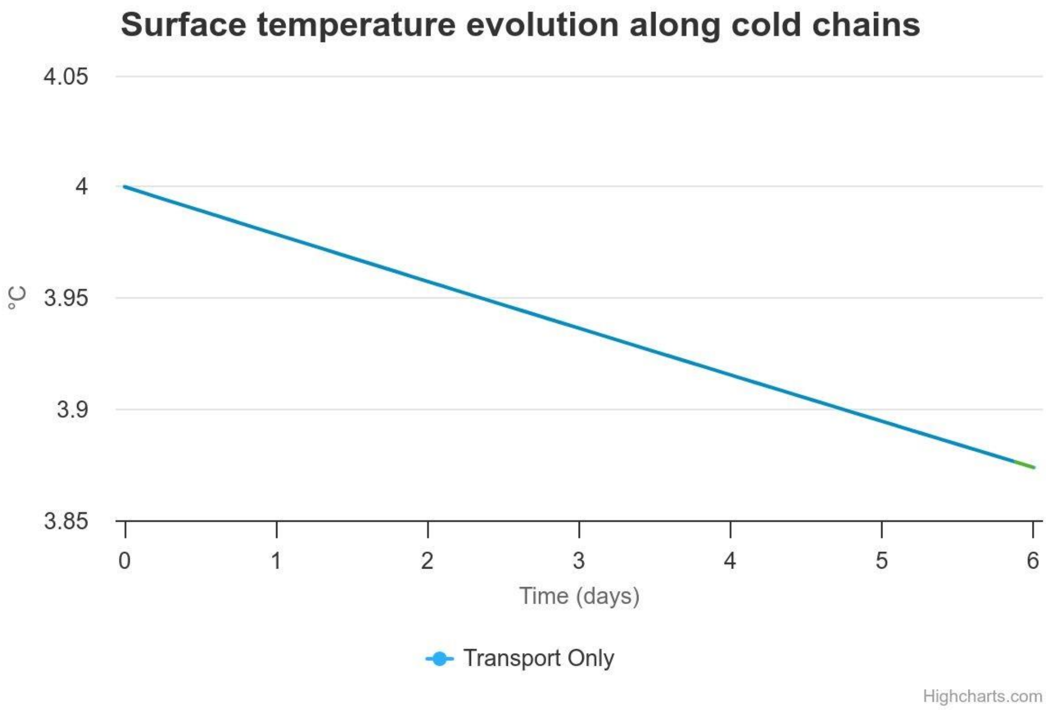


Figure 25: Surface temperature of salmon along the cold chain simulated in the ENOUGH tool

One factor not mentioned yet is the by-product utilization in market (BUiM). A higher share of BUiM reduces the GHG emissions of the products, as a higher share of GHG emissions can be attributed to the by-products. This would have been relevant if the processing step would have been included in the investigation, but it was left out due to the before mentioned reasons.

2.6.6 Conclusion

The ENOUGH tool is a tool to evaluate greenhouse gas (GHG) emissions along the food supply chain and to provide insights on the most valuable actions to save GHG emissions and/or product quality. Within this work, a salmon cold chain, originally investigated in a report by Winther et al. [39], was simulated to compare the results against each other. The report by Winther et al. [39] investigated the GHG emissions from Norwegian seafood products along their entire food chain. The chosen salmon cold chain was salmon fillets (B-trim) being transported by road and ferry from Norway to Paris. It was found that for the made assumptions and inputs, the ENOUGH tool estimates the GHG emissions lower than the report by Winther et al. [39] in the investigated categories of packaging and export. The cold chain step export consists of transportation and refrigeration within the ENOUGH tool, and refrigeration was found to be responsible for 2.6 % of the overall estimated GHG emissions. Hence, this implied that the overall factor calculating the emissions per t.km differs between the report and the tool, and further investigation is required for the made assumptions behind the tool and the report.

It is evident that the ENOUGH tool is work in progress, and throughout the work, several areas for improvement are found. The processing step is currently modelled as a cold store process in the ENOUGH tool, whereas in reality, refrigerated sea water is utilized to process salmon. Furthermore, no additional GHG emission parameters are included for emissions related to other than energy consumption of the refrigeration system. Such factors from reliable sources should be implemented in the tool for further versions.

One major difference between the ENOUGH tool and the report investigated in this study is the ability of the ENOUGH tool to take the food product quality into account. This is seen as an important feature as ensuring that the quality is not worsened when implementing low emission technologies will be key for the industry. For transportation, the product temperature is modelled based on a cold store process, with a certain stocking density and heat transfer coefficient. However, fresh fish is usually transported on ice and the cooling effect of ice is not yet implemented in the tool, which affects the product quality and energy consumption. In a further update, simplified correlations on the temperature decrease of salmon stored on ice and the changed thermal inertia in the truck could be implemented based on the ratio of ice/water.

Norway is a major global salmon producer, with a complex supply chain including feed production, salmon farming, processing, and transport. Most Norwegian salmon is exported fresh to Europe and Asia, with a small portion sold frozen. This case study compared the ENOUGH tool to a SINTEF report, focusing on a salmon cold chain from Norway to Paris. The study found areas for improvement in the ENOUGH tool, particularly in **modelling processing steps and accounting for ice cooling during transport**. One major difference between the ENOUGH tool and the report investigated in this study is the ability of the ENOUGH tool **to take the food product quality into account**. This is seen as an important feature as ensuring that the quality is not worsened when implementing low emission technologies will be key for the industry.

2.7 Replacement of salmon processing country

2.7.1 Introduction

The global fish industry plays a vital role in food security, providing essential protein and micronutrients for billions of people. However, its environmental impact is a growing concern. Capture fisheries and aquaculture (fish farming) are the two main sources of fish for human consumption. The FAO provides valuable data on global fisheries and aquaculture production [36].

Fishing, fish farming, fish processing and products transportation activities directly contribute to greenhouse gas emissions, primarily CO_2. The research on the impact of fish processing, transportation, and refrigeration on CO_2 emissions should be analysed to provide a holistic view. A comparison of CO_2 emissions from the EU's fishing and aquaculture sectors with global figures can reveal areas where the EU might be leading in terms of efficiency or where there's room for improvement.

The main causes of food discarding among consumers and retailers are the food aspect, outdating, and safety uncertainty. Damage and spoilage of foods lead to around 15% of waste, which increases to 35% if food is subject to inadequate storage and transport conditions. Fresh fish and shellfish are highly perishable products due to their biological composition. Fresh fish is stored, transported and distributed in boxes of high-density poly-ethylene filled with ice [49]

The efficiency of the fish production industry is crucial for achieving sustainable production and carbon neutrality, with a focus on energy efficiency, waste reduction, and resource usage evaluation[50]. Energy use and associated greenhouse gas emissions in fish processing have been analysed, highlighting the importance of energy requirements for different processing stages[51,52].

2.7.2 Case study description

The case study concerns the processing salmon cold chain that considers the Norwegian salmon from the initial chilling and processing of the salmon, the chilled storage and transport to Lithuania for further processing or direct consumption by consumers. The building of the cold chain was done using the Enough tool and the data from references. Cold chain data for the chosen salmon cold chain was obtained using the report by Winther et al. [11]. This data was used to simulate the cold chain using the ENOUGH tool. The cold chain was simulated and the results in terms of $kgCO_{2e}$/kg product presented.

The following section presents the set inputs and parameters to the ENOUGH tool for the specified cold chain from Norway to Lithuania.

The two Scenarios were chosen to analyse the impact on fish product environmental performance.

Scenario 1 describes Salmon product flow with fish processing to “Whole fish to head on gutted” in Norway and final processing in Lithuania (Fig. 26). In Lithuanian factory “Whole fish to head on gutted” is further processed to final edible salmon fillet ready for consumption.

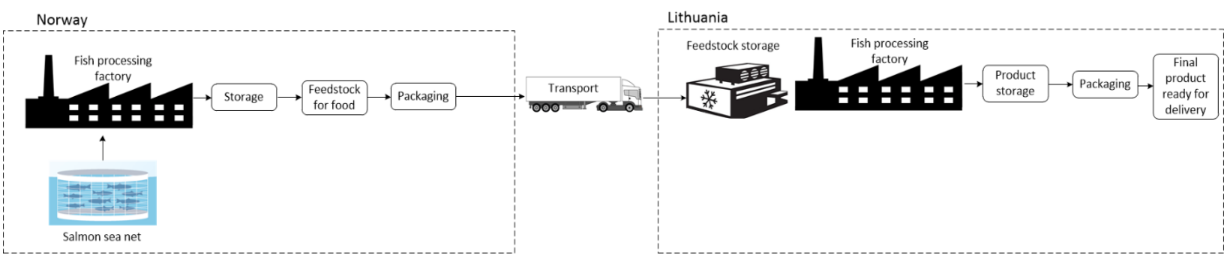


Figure 26. Salmon product flow diagram with fish processing in Norway and final processing in Lithuania

Scenario 2 - Salmon product flow with fish processing in Norway to edible salmon fillet ready for consumption and transportation of final products to Lithuania (Fig. 27).

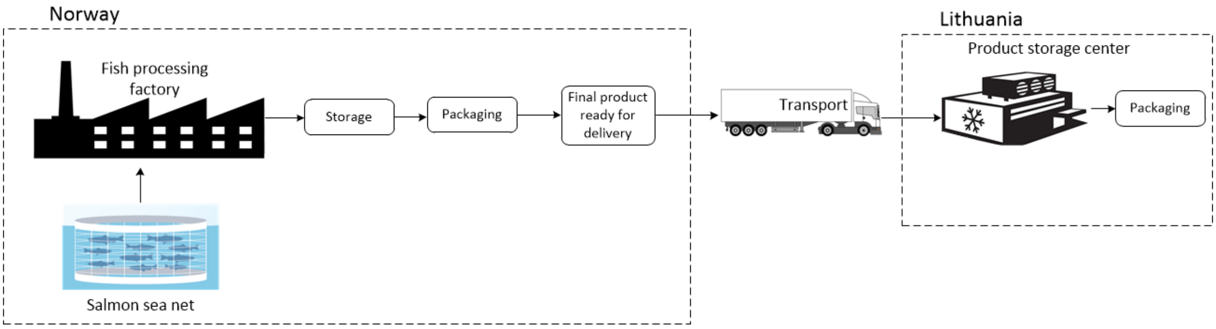


Figure 27. Salmon product flow diagram with fish processing in Norway and transportation of final products to Lithuania

Table 6 shows specific detailed information of the salmon cold chain. Other data needed for simulations were used from Chapter 2.1 and 2.6 of this report.

Processing is modelled in the ENOUGH tool within the block "Processing and Packaging". This step simulates the "processing and packaging" step as a cold store process, which calculates GHG emissions based on energy consumption of the refrigeration system to maintain a certain air temperature within the production facility.

In the current situation, fresh salmon arrives at the factory and is pre-cooled from approximately sea water temperature to 8 °C. Afterwards, salmon is chilled through RSW chilling and bled out. Subsequently, processing and packaging takes place, where fresh salmon is stored on ice.

Packaging

The salmon was packaged in an EPS box with ice. The tool differentiates between primary, secondary and tertiary packaging, and requires information thereof to quantify the GHG emissions related to packaging. The report by [8] specifies secondary packaging by means of EPS boxes with a thickness of 40 mm [9]. Tertiary packaging is assumed to be EPS boxes wrapped together by thin plastic foil on palettes. It was assumed that the plastic foil has a thickness of 0.01 mm. The final edible product after final processing in Lithuania or in Norway was assumed to be packed in primary packaging of average plastic with thickness of 0.3 mm.

Transport

The chosen salmon cold chain simulated in the current case study was fresh or produced salmon transported to Lithuania by road and ferry. For both Scenarios, the transportation distance according to Google maps was 1418 km by road and 275 km by sea. Road transportation where an average speed of 50 km/h, with 9 h driving time per day is assumed. So called Roll on roll off (Roro) ferries were used as part of truck transports (e.g. for trucking from Sweden to Denmark and from Sweden to Latvia).

Table 6: Detailed information of the simulated cold chain.

	Unit	Scenario1	Scenario 2
Product		whole fish to head on gutted	whole fish to E-trim - skin and boneless fillet. Edible product
Energy		Norwegian electricity CO_2 emission factor for processing in NO and European factor for processing in Lithuania	Norwegian electricity CO_2 emission factor for processing in NO and European factor for processing in Lithuania
Transport Type 1			
Vehicle category		road - articulated truck 40 t	road - articulated truck 40 t
Fuel type		Diesel	Diesel
Distance (km)	km	1418 (Trondheim – Raseiniai)	1418 (Trondheim – Raseiniai)
Duration (days)	day	3.151	3.151
Transport type 2		Sea ferry (275 km) – Nynashamn - Ventspils	Sea ferry (275 km) – Nynashamn - Ventspils
Distance (km)	km	275	275
Vehicle category		Sea – Ro-Ro fleet average	Sea – Ro-Ro fleet average
Fuel type		Heavy Fuel oil	Heavy Fuel oil
Duration (days)	day	0.583	0.583
Packaging			
Type of packaging		Primary (Plastic average)	Primary (Plastic average)
		Secondary (Expandable polystyrene EPS box) Dimensions (mm): 800x400x195. EPS, wight per box =0.60 kg	None
		Tertiary (Plastic average), 0.01 mm	Tertiary (Plastic average), 0.01 mm

Two cold chains were modelled in ENOUGH tool (Figure 28 and Figure 29).

Figure 28: Building the salmon cold chain using Enough tool for SC1

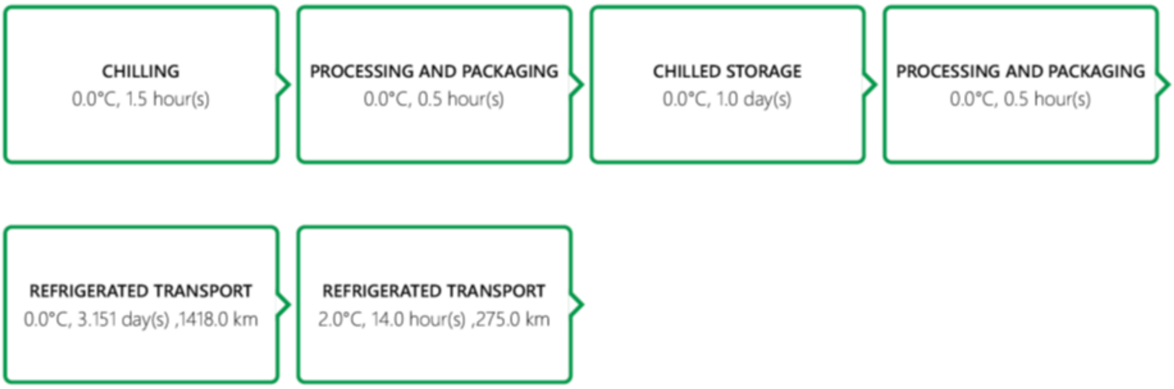


Figure 29: Building the salmon cold chain using Enough tool for SC2

2.7.3 Simulation results, benchmarking the tool

Processing refers to the filleting, freezing, peeling, salting, drying of fish to seafood products. Data for yields of salmon product was used from [8]. It was assumed, that yield of salmon to "whole fish to head on gutted" is 0.822 kg/kg, and final "Whole fish to E-trim - skin and boneless fillet. Edible product" – 0.450 kg/kg. The mass flow must be taken into account, because the different mass quantities needs to be transported in different Scenarios. If whole fish to head on gutted is transported, then only part of it becomes whole fish to E-trim - skin and boneless fillet, edible product. Thus the model was developed in the way, that to reflect the final edible product to be in Lithuania. In that case, to get the same mass of edible final product we need to transport more whole fish. The ratio in which we need more whole fish to transport was calculated based on the calculation: 0.822 kg/kg / 0.450 kg/kg = 1.826. It means that we need to transport 1.826 kg of whole fish to get final edible product of 1 kg in Lithuania. In the case of Scenario 2, we transport already prepared final edible product, thus this ratio equals to 1.

Preliminary studies indicate that packaging in EPS boxes could increase CO_2 emissions dramatically, thus it was decided to check the emissions if companies could replace EPS boxes to cartonboard boxes. In such case we developed SC1-Carton scenario.

Figure 30 presents the CO_2 emissions of the salmon cold chain of three scenarios obtained by the tool. The impact of packaging is highest in both Scenarios (SC1 and SC2). The packaging impact has lower

CO_2 emission in SC2 than in SC1 due to the fact, that EPS boxes are used only in SC1 when whole fish to head on gutted is transported as semi-product for further processing.

Packaging accounts for 67.4 % of the total emissions in SC 1. However, replacing EPS to cartboard reduces emissions to 14.3 % of total emissions in SC1.

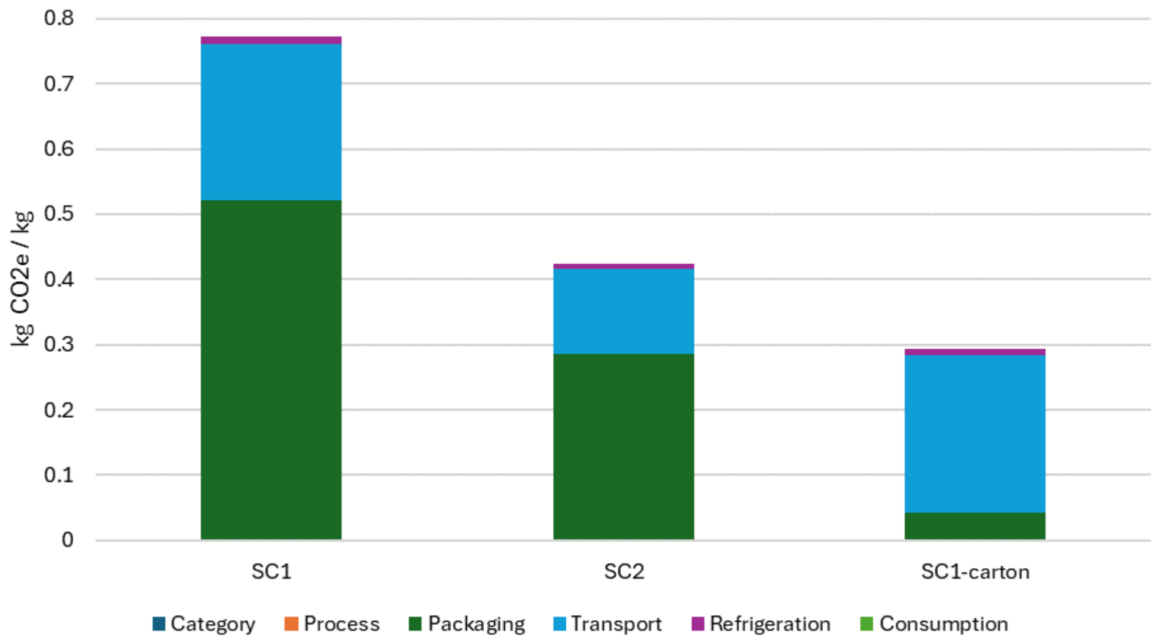


Figure 30: Benchmarking of the CO_2 emission of three scenarios of salmon cold chain

The data shows that packaging contributes significantly to CO_2 emissions, with EPS (Expanded Polystyrene) boxes being the main culprit. Replacement EPS with cartonboard packaging, which has a much lower carbon footprint, companies can drastically reduce emissions from packaging.

Implementation of reusable packaging systems where EPS boxes are collected, sanitized, and reused would further reduce the need for new packaging materials, thus cutting down emissions associated with their production and disposal.

In this case study, the analysis shows that **transporting whole fish** requires more mass to achieve the same amount of edible product in Lithuania, leading to higher emissions. **By processing the fish closer to the point of origin and transporting only the final edible product,** companies can reduce the volume of goods transported, thereby lowering packaging needed, fuel consumption and environmental impact, reducing CO2 equivalent emissions **by 47%**. These emissions could even reach **63%** by switching to packaging with lower carbon footprint.

3 CONCLUSION

The benchmarking studies carried out in this deliverable using the ENOUGH tool highlight the significant potential for reducing greenhouse gas (GHG) emissions within food supply chains. The simulations show that significant emission reductions can be achieved by integrating low-emission technologies, switching from overseas to local products, optimising transport methods (e.g. switching from air to sea transport) and implementing alternative packaging solutions such as cardboard instead of expanded polystyrene (EPS).

The case studies presented here show that strategic choices in packaging, processing and transport do not only reduce emissions but also can preserve product quality. For example, switching from EPS to reusable or recyclable cardboard packaging, or from fresh salmon transported by air to frozen salmon transported by sea, resulted in reductions of emissions from 10 to 90% while maintaining the freshness and safety of highly perishable products such as salmon. The use of low-emission technologies such as those selected in Work Package 2 of the project, such as improved refrigeration systems and transport optimisation, further enhances these environmental benefits allowing global reductions of emissions ranging from 38% to 90%.

The ENOUGH tool provided a valuable platform for conducting these studies and comparing GHG emissions under different cold chain scenarios. One of the key advantages of the ENOUGH tool over traditional Life Cycle Assessment (LCA) tools is its specific focus on dynamic modelling of cold chain logistics, providing real-time, quality, energy consumption and emissions results. Unlike many LCA tools that provide a more static, top-down view of GHG emissions over an entire lifecycle, the ENOUGH tool allows for a more granular approach, assessing each individual step in the cold chain and providing suggestions to reduce their carbon footprint. In addition, the ENOUGH tool incorporates product quality as an assessment criterion, which is a significant advantage for industries dealing with perishable goods. By dynamically simulating time-temperature correlations throughout the cold chain, it provides insight not only into the environmental impact, but also into the preservation of food quality. This is a unique feature compared to standard LCA tools, which often do not account for quality degradation or time-sensitive variables. In terms of user experience, the ENOUGH tool is designed to be highly accessible and user-friendly, offering scenario modelling that can be adapted by non-expert users to explore different emission reduction strategies. Traditional LCA tools often require significant expertise in both environmental science and data management, limiting their use to specialists. The ENOUGH tool, on the other hand, provides a more intuitive platform, enabling wider adoption across industries, decision makers, students, and more generally by a broad non-specialist audience.

In conclusion, the case studies presented in this document and the methodology used highlight the importance of adopting comprehensive strategies that encompass all aspects of the supply chain. By addressing inefficiencies in packaging, transport and refrigeration, companies can achieve a greener and more sustainable food supply system. Future work should continue to refine tools such as the ENOUGH tool to include more products and advanced methodologies.

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