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LCA of pork products & evaluation of alternative super-chilling techniques

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Preface

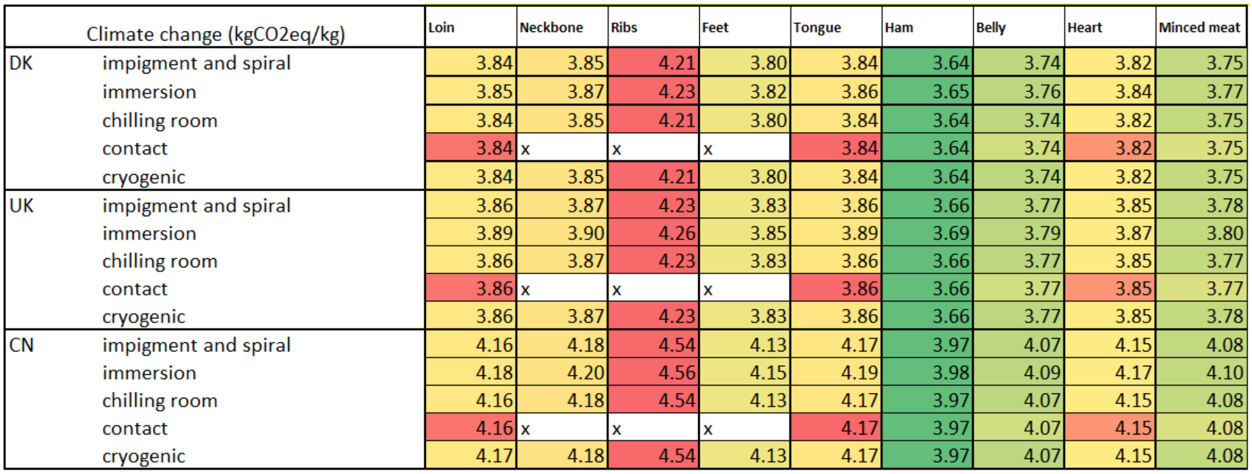
This is report represents deliverable 4.3 of the project “Bæredygtigt svinekød til det globale marked” (GlobalMeat) funded by the Ministry of Environment and Food of Denmark, The Danish AgriFish Agency (journalnr.: 34009-13-0699)

Executive summary

This LCA study has two aims: 1) The environmental assessment of Danish pork products (Danish Landrace breed): The purpose is to put the pork production system into perspective and to identify the relative contribution of different life cycle stages; 2) The comparative assessment of alternative after cooling technologies, which affect the products' shelf life: The purpose is to identify the technology leading to least environmental impacts in a life cycle perspective; also to facilitate a benchmarking of these technologies relative to existing after-cooling approaches i.e. freezing.

To fulfil the double aim a farm-to-consumer LCA of pork-products headed for human consumption was performed. Nine alternative pork products were identified, i.e. front feet, neck, ribs, loin, processed loin, hearts, tongues, minced meat, belly. Additionally, five alternative after-cooling technologies were considered. These are either already used on an industrial scale (chilling rooms, spirals, impingement) or are new innovations under development (immersion, contact).

GlobalMeat project partners provided inputs to define the technical specifications of the system. Foreground data has been collected for the processes related to the meat processing plant (processes, outputs, handling of by-products), cooling, packaging and transport (in terms of distances and cooling requirements). The transport to three alternative markets (Denmark, United Kingdom and China) was evaluated. Data for pig raising/farming was taken from literature. An attributional modelling approach was followed and Multi-functionality (related to by-products such as feed) was handled through system expansion. The impacts of the total system were distributed to the different pork products on the basis of mass allocation. The climate change impacts per kg product for the different scenarios are given here bellow:



Climate change (kgCO2eq/kg)		Loin	Neckbone	Ribs	Feet	Tongue	Ham	Belly	Heart	Minced meat
DK	impigment and spiral	3.84	3.85	4.21	3.80	3.84	3.64	3.74	3.82	3.75
	immersion	3.85	3.87	4.23	3.82	3.86	3.65	3.76	3.84	3.77
	chilling room	3.84	3.85	4.21	3.80	3.84	3.64	3.74	3.82	3.75
	contact	3.84	x	x	x	3.84	3.64	3.74	3.82	3.75
	cryogenic	3.84	3.85	4.21	3.80	3.84	3.64	3.74	3.82	3.75
UK	impigment and spiral	3.86	3.87	4.23	3.83	3.86	3.66	3.77	3.85	3.78
	immersion	3.89	3.90	4.26	3.85	3.89	3.69	3.79	3.87	3.80
	chilling room	3.86	3.87	4.23	3.83	3.86	3.66	3.77	3.85	3.77
	contact	3.86	x	x	x	3.86	3.66	3.77	3.85	3.77
	cryogenic	3.86	3.87	4.23	3.83	3.86	3.66	3.77	3.85	3.78
CN	impigment and spiral	4.16	4.18	4.54	4.13	4.17	3.97	4.07	4.15	4.08
	immersion	4.18	4.20	4.56	4.15	4.19	3.98	4.09	4.17	4.10
	chilling room	4.16	4.18	4.54	4.13	4.17	3.97	4.07	4.15	4.08
	contact	4.16	x	x	x	4.17	3.97	4.07	4.15	4.08
	cryogenic	4.17	4.18	4.54	4.13	4.17	3.97	4.07	4.15	4.08

1) **The environmental assessment of Danish pork products (Danish Landrace breed)**: The results showed that the impacts to climate change, acidification and eutrophication (the impact categories identified as most relevant for meat products by the draft PEFPCR) are approximately 3.9 kgCO2eq/kg, 0.07 molc H+ eq/kg and 0.34 molc N eq/kg respectively. A 8% increase can be expected due to evaporative and dripping

losses. Considering climate change, the results from this study are consistent with other literature, where values typically range from 3.1-3.6 kg CO2-eq (Dalgaard 2007; Stephenson 2010; Nguyen et al. 2011; Reckmann 2013; Reckmann et al. 2013). In terms of hotspots, farming is the dominant environmental hotspot in the product life cycle, contributing approximately 90% to all three impact categories. Consequently, the total impact from pork is less sensitive to changes within the other life cycle stages. This lack of sensitivity also relates to the alternative cooling technologies; after-cooling only marginally affect the overall LCA results.

2) **The comparative assessment of alternative after cooling technologies**: Comparing the alternative technologies on the basis of 'cooling 1 kg of each product', the use of conventional chilling rooms and then novel technology 'contact' perform better. However, contact is less flexible since it requires that the cuts have a regular shape, for example the technology can not be used for cooling pork feet. The impact from immersion is significantly higher than the rest due to the soft plastic used to wrap the cuts prior to passing through the cooling medium. The comparison of the different technologies does not account for other decision criteria, such as costs and physical space requirements, which need to be co-evaluated in order to conclude on the most preferable option.

Super chilling performs environmentally better than freezing by a factor of 3 due to the lower energy consumption. The technology also allows fresh meat to reach distant markets since it extends the shelf life by more than a factor of 3 compared to fresh meat. Additionally, there is evidence that an extension of the shelf life leads to reduced food waste. In UK it is estimated that an increase of just one day could help prevent 5% of avoidable food waste. Yet transport overseas implies less availability of the products to the retailer as more of the total product life is using during the transportation stage. For instance if the retail temperature is 5°C and that the retailer keeps the products for a week, transport of fresh products to China is possibly not viable from a food safety perspective since the transport time (approx. 25 days) would exceed the shelf life (17-22 days).

Contents

1 Introduction

The steady increase in the human population and standard of living has led to a higher global demand for meat (Dalgaard 2007; Vergé et al. 2012; Reckmann et al. 2013). This, along with technological development, has created a commercial model where high quality meat can reach the furthest consumer markets, irrespective of the production site. In Denmark, agricultural product based revenue is to a large extent based on pig meat/pork supply chains, where the annual pork production processes approximately 28 million pigs (DAFC 2016). Danish Crown and Tican Fresh Meat A/S meat processing plants process 90 % and 7 % of the pigs in Denmark, respectively (Hamann 2006). In 2012/13 Danish Crown processed approx. 14.8 million pigs and sows in Denmark and Danish Crown subsidiaries in the UK, Sweden and Poland processed approx. 6.3 million pig during the same time period (DC 2016a). As 90 % of Danish pork production is exported, there is a 17 % possibility that a global consumer's next pork purchase is exported pork from Denmark (Hamann 2006).

Given the magnitude of production, it is relevant to assess the environmental impacts related to the production and processing of pork. Life Cycle Assessment can be employed for such an assessment using the ISO standardized state of the art environmental impact assessment methodology. It captures the life cycle of products and systems from cradle to grave (i.e. raw material extraction, manufacturing, use stage, final disposal); it accounts for the emissions and wastes associated with the corresponding processes; and it further translates these emissions and wastes into a wide range of potential environmental impacts (ISO 2006a; ISO 2006b). LCA allows for a systemic approach to environmental management, avoiding sub-optimisations or shifting the problems in space (such as moving production from one country to another) and time (such as by postponing the environmental management tasks and therefore passing the burden onto future generations).

LCAs of pork products have been reported in scientific literature with at least 10 LCAs having being performed on European pork (Dalgaard 2007; Reckmann et al. 2012; Reckmann et al. 2013; González-García et al. 2015). There are two limitations identified in the existing literature related to:

1) The environmental impacts considered: Most of the studies are commonly focusing on single environmental impact categories such as climate change, i.e. in the form of carbon footprint. Such single impact category approaches, although valuable (e.g. they respond to the current need for climate change mitigation), only provide a fragmented picture of the environmental impacts associated with a product. This risks shifting the burden to other environmental impact categories (ISO 2006a).

2) The boundaries of the assessed systems: Most of the studies have focused on the production approaches which cover the supply chain from the farm to the final product (i.e. so-called cradle-to-gate LCAs). Conclusions drawn from these are that raising of pigs (pig feed production) is the most environmentally burden intensive part (Dalgaard et al. 2007; Reckmann et al. 2013; González-García et al. 2015). This observation has led to several changes to the condition that pigs are raised under, thereby lowering the environmental footprint at the farm level. On the other hand, few studies have

focused on the technology that is applied when processing the meat. Improved processing technology can also lead to lower energy consumption; lower residues; and eventually a longer shelf life at the market and hence lower food waste (Lee and Osborn, Steve Whitehead 2015).

In this sense, the post -slaughterhouse after-cooling processes for regulating the temperature of the meat products so that these are preserved in adequate quality until they reach the retail markets are of particular interest. Meat products can be preserved by refrigeration at three different states: fresh, frozen, or super-chilled. In the latter case, the temperature of the product is lowered to just under its freezing point. After an initial surface freezing, the ice distribution equilibrates and the product obtains a uniform temperature at which it is maintained during storage and distribution (Magnussen et al. 2008).

Although super-chilling had already been described in 1920, it still remains in a grey area in international legislation since food is considered to be frozen typically when it is below -12 °C. (Zhou et al. 2010; Kerry and Kerry 2011). Thus, super-chilling is commonly used but often not declared as such. For instance, in the U.S. the legal temperature specification for chicken is that if the temperature is above -3.3° C, the product must be labelled as fresh. Confusingly, other terminologies, such as deep-chilled, ultra-chilled, hard-chilling, partial-freezing, sub-cooled and super-cooled, are also used to describe the temperature range which is close to but just above the freezing point. The advantage of this temperature range is that it is low enough to reduce bacterial activity but high enough to avoid levels of crystal growth that can cause structural damage to the meat (Kerry and Kerry 2011).

Despite the discrepancies in terminology, super-chilling has commonly been used in seafood (Olafsdottir et al. 2006; Beaufort et al. 2009; Zhou et al. 2010). It is now being used more frequently in other meat products as it has been estimated that the technique can prolong the shelf life for a meat product for 1.4 – 4 times when compared to conventional meat-chilling methods. However, it may result in some increase in product drip during storage (Magnussen et al. 2008; Schubring 2009) and, compared to freezing at -20 °C, super chilling may cause minor structural changes, due to the formation of ice crystals during storage at subzero temperatures (Lee and Toledo 1984).

1.1 Objective of study

With this background, this LCA study aims to assess different pork products by investigating the technological improvement potential of introducing new after-cooling technologies. The market segment under investigation is the supply of fresh pork meat with an extended shelf life to foreign markets (GlobalMeat 2013). This overall aim can be broken down to two studies:

1) The environmental assessment of Danish pork products (Danish Landrace breed): The purpose is to put the pork production system into perspective and to identify the relative contribution of different life cycle stages and corresponding improvement potentials.

2) The comparative assessment of alternative after cooling technologies, which affect the products' shelf life: The purpose is to identify the technology leading to least environmental impacts in a life

cycle perspective; also to facilitate a benchmarking of these technologies relative to existing after-cooling approaches i.e. freezing.

To fulfil these two aims, a farm-to-consumer LCA of pork-products headed for human consumption was performed. Nine alternative pork products were identified, i.e. front feet, neck, ribs, loin, processed loin, hearts, tongues, minced meat, belly. Additionally, five alternative after-cooling technologies were considered. These are either already used on an industrial scale (chilling rooms, spirals, impingement) or are new innovations under development (immersion, contact) (GlobalMeat 2013). The LCA aimed to unveil the environmental impacts of the different pork products and to report on the environmental performance of the new proposed after-cooling technologies compared to existing options (i.e. freezing). The results can be used by producers, retailers, researchers and other stakeholders in the meat industry to understand the relationship between meat processing, shelf life and environmental performance.

2 Goal and scope: products and system description

The LCAs were conducted according to the International Reference Life Cycle Data System (ILCD) Handbook for LCA (EC-JRC 2010). As a first step the goal (i.e. the purpose) and scope (i.e. what to analyse and how) were identified. The goals of the LCAs and the intended applications coincide with the research objectives in Section 1. In terms of scope, the functional unit (FU), which reflects the primary function of the system and is the basis of the LCA, was defined as "1 kg of pork products unpacked at consumer". To ensure technological and market representativeness, GlobalMeat project partners provided inputs to define the technical specifications of the system.

2.1 Product definition

The average weight of a live pig reaching the meat processing plant is estimated by Danish Crown to be 104.001 kg (Tingaard 2016). It is estimated that there is 7wt% (7.3 kg) loss between slaughter and retail sale due to evaporation of water (James 2002). The remaining 96.7kg contain 84% (81 kg) human-edible products (based on Danish Crown data given in Table 6). Weight specifications for selected products have been provided by DMRI and are given in Table 1. These add up to approximately 34kg. The remaining 47 kg include other meat cuts and other products such as liver, intestines, lungs, ears etc. (see also Appendix 8.1).

Table 1**.** Weight specifications of the assessed pork products. Based on standard values provided by DMRI for an average pig of 104 live weight.

	Weight (kg/pig)	% live weight
Tender Loin	1.28	1.2%
Neckbone	1.19	1.1%
Rib bones	0.57	0.6%
Minced meat (5-10%)	6	5.8%
Whole ham	15.74	15.1%
Belly (for Bacon)	7.87	7.6%
Tongue	0.24	0.2%
Heart	0.32	0.3%
Front feet	0.84	0.8%
Summary		
Cuts under assessment	34.1	32.7%
Other food products	47.19	45.4%
Evaporative losses	7.28	7.0%
Other by products	15.48	14.88%

2.2 System Boundaries and data requirements

The overview of the system boundaries considered for the assessment is given in Figure 1. This shows the different processes across the life cycle (e.g. farming and meat processing plant) and the different system outputs (i.e. products, co products and by-products). Due to the plethora of sub processes, further details of the different processes are provided in separate figures (Figure 4 and Figure 5).

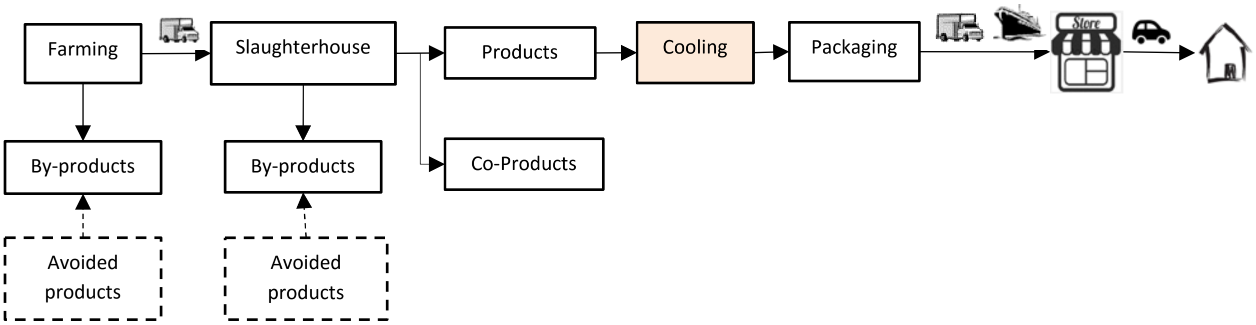


Figure 1. System boundaries

Foreground data have been collected for the processes related to the meat processing plant (processes, outputs, handling of by-products), cooling, packaging and transport (in terms of distances and cooling requirements). For modelling the background processes, e.g. electricity production, waste management etc., the study relied on generic data from ecoinvent v3.1 (Weidema et al. 2013). The plant at Horsens, Jutland, is the largely pork processing facility in the Danish Crown Pork group, and was used as the location for the purposes of transport calculations.

2.2.1 The issue of scaling up laboratory data

In new product (or technology) development projects, the maturity of the developed solution affects the LCA results. This is particularly relevant for early stage LCAs of emerging technologies, due to the need to upscaling data from lab-scale to industrial scale (Hetherington et al. 2014). Technology efficiency typically increases substantially in larger scale applications, as exemplified in Caduff et al. (2012) where increasing wind turbine size leads to higher power production and lower global warming potential. Other emerging technology areas, such as nanomaterial production, also show the same trends where environmental burdens are reduced as technology matures (Gavankar et al. 2015). The essence of the learnings from other technological domains is that either industrial scale data or approaches to upscale lab-scale data are needed (Wender et al. 2014). This LCA study is founded on primary lab-scale data of the new proposed after-cooling technologies, since these were still under development as part of the GlobalMeat (2013) project. However all the values used in this report have already been upscaled to correspond to the final industrial use based on DMRI dedicated technology upscaling models.

2.3 Modelling principle and handling Multi-functionality

This is a descriptive study that documents the analysed systems and possible product development decisions (e.g. for the future of cooling technologies). It is hence classified under decision context of situation A ‘micro-decision support’ of ILCD and an attributional LCA approach has been followed in accordance with ILCD guidance: ‘‘*The most appropriate LCI model for Situation A shall represent the supply - chain of the analysed system, applying attributional modelling’* (EC-JRC 2010). Large scale interaction with other systems (e.g. the detailed exploration of food markets and the long term consequences of changing meat consumption patterns) were out of scope.

The products of interest are presented in Table 1. However, the system under study is characterised by Multi-functionality, meaning that it provides more than one function (service) (EC-JRC 2010). As visualised in Figure 1 the system outputs include:

a) Products: the nine products under study
b) Co-products: other products that are the output from the meat processing plant and are suitable for the human consumption market ,; and
c) By-products: otherwise unwanted products and wastes that are typically further processed into secondary useful materials and energy. Such products include e.g. manure from the farm, parts of the intestines, unwanted hair/bristle, wasted fat etc.

This Multi-functionality needs to be handled so that only the appropriate inputs and outputs of the processes are included and system inputs and outputs consumed materials, resource flows, emissions, wastes, etc). are assigned to the different products, coproducts and by-products. The choice of allocation method will influence the final results as seen in Figure 2, which represents climate change impact from different meats. The figure also shows that compared to other meat, in terms of potential contribution to climate change, pork is less burdensome than beef and lamb, which is also consistent with the findings of other literature (Reckmann 2013).

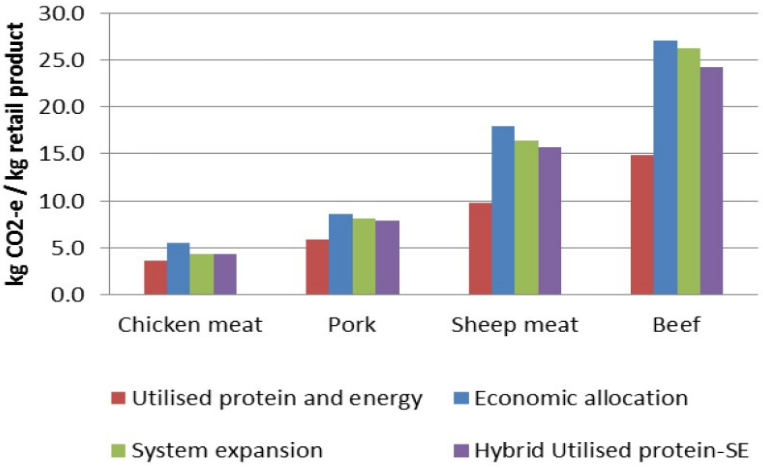


Figure 2 Greenhouse gas emissions for different kinds of meat, according to different ways of performing allocation (Wiedemann and Yan 2014)

2.3.1 Multi-functionality across products, by-products and co-products

According to ILCD, the most preferable approach for addressing Multi-functionality is to subdivide one multifunctional process into many mono-functional ones. This implies that one can clearly distinguish the consumed materials, resource flows and emissions that correspond to each function. This approach is not feasible in the product system under study. For instance, focusing on farming it is not clear how much feed goes to the production of loin (product), of lungs (co-product) or of hair (by-product). Therefore this study employs the second option in the allocation hierarchy, that of system expansion, in accordance to what ILCD suggests: "*For cases of system - system relationship and multi-functionality of processes and products that cannot be solved by subdivision or virtual subdivision, the system expansion approach shall be adopted , substituting the avoided process as its market mix (excluding the to - be - substituted function/route)"* (EC-JRC 2010).

With this approach, the system boundaries are expanded to include an alternative provision of the non-required functions of the by-products. The system is then credited with the avoided impact from the alternative process that the required function replaces. For example, the unwanted manure from farming is used as fertiliser and therefore, a certain amount of artificial fertiliser that would otherwise be required will now be avoided. The system can therefore be credited with this avoided production of artificial fertiliser. The system expansion used to account for the by-products and co-products is visualised as "avoided production" in Figure 1.

The benefit of using this approach is that it is consistent with other literature (Vergé et al. 2012; Reckmann et al. 2012; Wiedemann and Yan 2014). Additionally, Dalgaard et al. (2007) employ system expansion when assessing the impacts from pork farming. Note that this latter study has provided the background data for the farming processes, as decided by the project partners in the GlobalMeat project. Therefore, keeping the same approach for handling Multi-functionality ensures coherence throughout the assessment. On the other hand, one challenge arising from following this approach is due to the nature of the products. No alternative production/process exists for the exact function. For instance the heart and liver are always together, so there is no alternative production of a pig liver. In such cases the ILCD guidance allows for a substitution of the function that the by-product provides , i.e. livers from other animals can be assumed to be superseded. Consequently, data were collected to represent the "average animal" (see Table 9).

2.3.2 Multi-functionality within 'products'

Aside the substitution of by-products, the impacts will also need to be assigned to all the edible parts. There are parts of the system that can be isolated so that processes can be directly linked to the output e.g. this is the case of the processed meat, where only the ham undergoes a cooking process. It is also the case for some of the meat processing plant processes, for example 'organ processing' is only relevant for the organ products such as the heart.

However, there are parts of the system where it is not possible to distinguish the causal chain between process and output (e.g., it is not possible to distinguish which part of animal feed goes to 'heart' or to 'ham'). For these parts of the system, the environmental impacts need to be split between the products according to some allocation criterion. This should ideally be based on causal-physical relationship between products. As a reference case, following the PEFPCR (Product Environmental Footprint- Product

Category Rules) recommendation for the assessment of meat products (TS 2016), weight has been used an allocation key (see Table 7). Economic allocation based on market price is commonly used in meat LCA studies (Canals et al. 2002; Cederberg and Flysjö 2004; Basset-Mens and van der Werf 2005; Williams et al. 2006; Hirschfeld et al. 2008; Ledgard S. F. et al. 2010; Opio et al. 2013), however in the present study it was not used not only because it is the option least recommended by ISO, but also because market prices are volatile and inhomogeneous across regions (e.g. the heads are considered a delicacy in China and sold at a high price while in Denmark they are considered an undesired by-product) thus the results could lack representativeness and would be quickly outdated due to changes in market prices. The draft PEFPCR came to the same conclusion and discourages the use of economic allocation.

2.4 Impact assessment

The impact assessment has been performed for all the 14 environmental impact categories given in Figure 3. For each category the assessment has been done following the ILCD recommended life cycle impact assessment (LCIA) methodology (Hauschild et al. 2013).

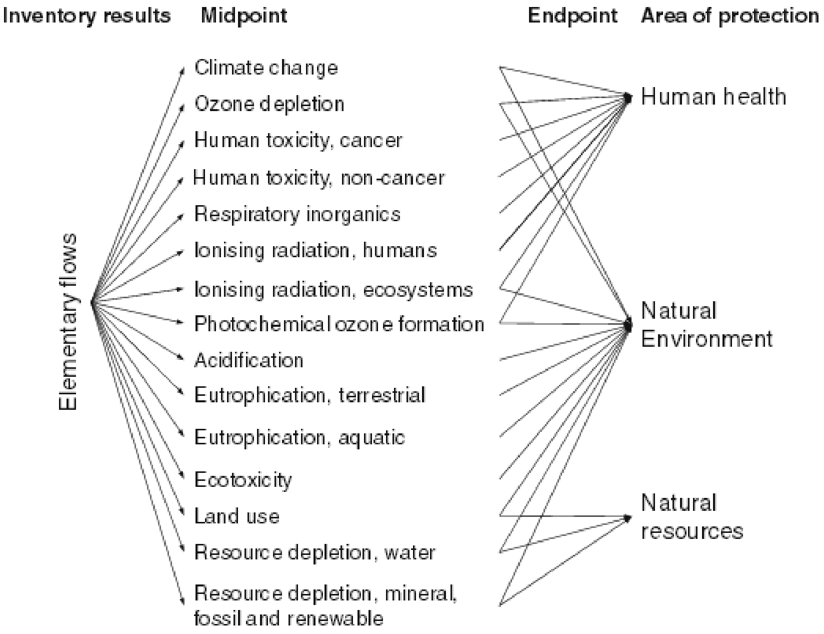


Figure 3. Mid- and end-point environmental impact categories assessed (Hauschild et al. 2013)

Of primary interest was the system's contribution to the impact categories given in Table 2 in accordance to the draft PEFPCR for meat products (TS 2016). The systems were modelled using SimaPro software v.8.1.

Table 2. Main impact categories of focus per PEFPCR for meat products (TS 2016)

Impact category	Main contributing elementary flows
Terrestrial eutrophication	Ammonia at farm and cultivation > 90% rest is energy related
Acidification	Ammonia at animal farm and cultivation >80 %, rest is energy use related NOx, Sox

Climate Change	CH_4, CO_2 from LUC, N_2O, fossil carbon related emissions

3 Inventory data collection and modelling

Life Cycle Inventory (LCI) data for the processes occurring during animal raising, in the slaughterhouse, after the slaughterhouse up until the products reach the consumer, are given in this section. Each of the subsections also discusses how Multi-functionality has been handled. All the inventory processes modelled are given in Appendix 8.6.

3.1 Animal raising

Data for pig raising/farming is taken from Dalgaard et al. (2007). It is representative for the average pig raising conditions for the average Danish breed (Danish Landrace), where anaerobic digestion of manure/slurry is used and biogas generated in the digestion process is used to replace fossil fuel energy. Figure 4 shows the processes for farming and Table 2 lists the corresponding inventory data.

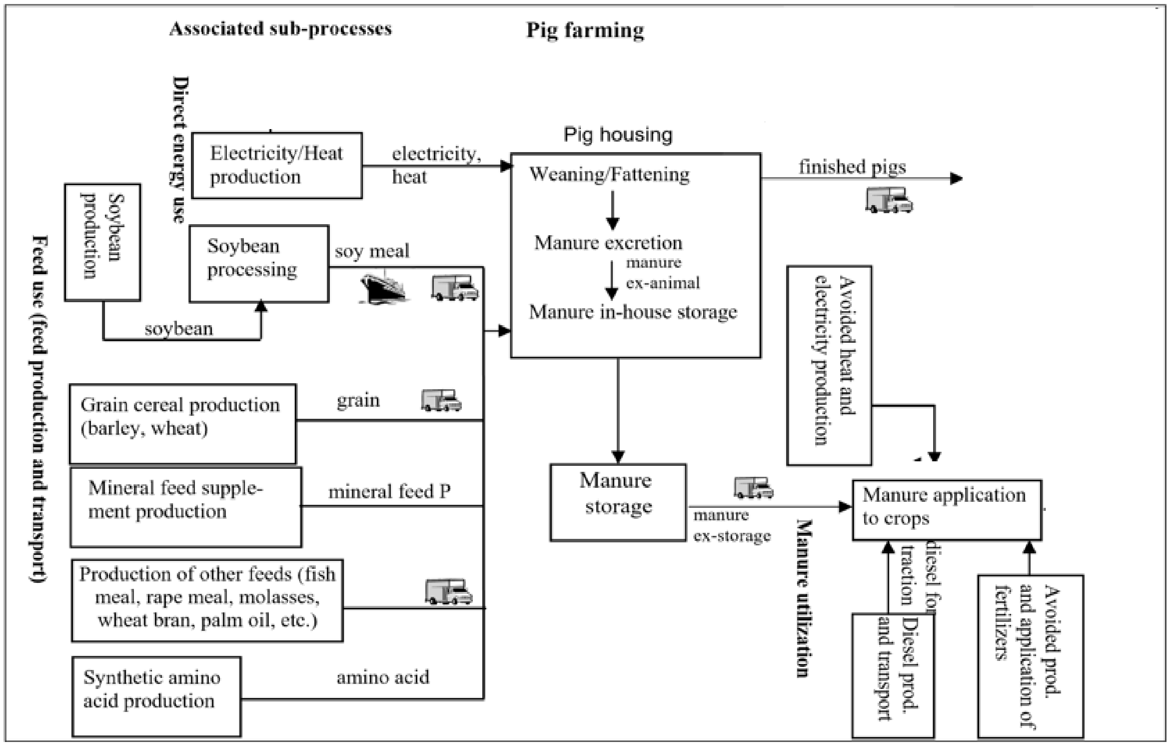


Figure 4. Overview of the product chain of Danish pork (adapted from Nguyen et al., 2010).

Table 3. Life cycle inventory per tonne live animal (at farm gate) corresponding to typical 2010 production.

Item	Unit	Per tonne live animal
Feed use	kg	
Wheat		1112
Barley		855
Soybean meal		341
Others		497

Mineral feed P		1.8
Transport of feed [a]	tkm	
By truck		411
By ship		4094
On-farm energy use [b]		
Electricity	kWh	148
Heat	MJ	541
Manure flow [c]		
Mass ex-animal/ex-housing/ex-storage	t	6.9/6.9/7.4
DM (Dry Matter) ex-animal/ex-housing/ex-storage	Kg	528/502/477
VS (Volatile solids) ex-animal/ex-housing/ex-storage	Kg	433/406/381
N (Nitrogen) ex-animal/ex-housing/ex-storage	Kg	45.3/39.0/37.5
P (Phosphorous)	Kg	7.9
K (Potassium)	Kg	20.6
On-farm emissions [d] CH_4	Kg	
(Enteric fermentation)		(3.7)
(Manure management)		(16.2)
N_2O (in-house and outside storage)	G	553
NH_3	Kg	7.6
NO_x	G	612
Manure utilization for fertilizers		
Transport to fields [a]	tkm	75
Farm traction [b]	MJ	157
N_2O emissions [d]	G	744
NH_3 [d]	Kg	8.4
NO_x[d]	G	123
NO_3 [d]	Kg	16.6
PO_4[d]	Kg	0.7
Avoided fertilizer production [e]	Kg	
from manure N		28
from manure P		7.7
from manure K		20.6
Avoided fertilizer application		
Farm traction [b]	MJ	11
N_2O emissions [d]	G	473
NH_3 [d]	Kg	2.2
NO_x	G	646

Transportation from farm to slaughterhouse

Based on Danish Crown data, the transport time to the slaughterhouse does not exceed 3 hours (DC 2016b). The journey times in Denmark fall well within the maximum permitted transport times, which allow for 8 hours without food and water. Considering a transport speed of 80 km/h for 3 hours, a transport distance of 240 km from farm to slaughterhouse is assumed.

3.2 Slaughterhouse

The slaughtering process (see also Appendix 8.3) is well described on the Danish Crown website (DC 2016b). The process begins in the Black slaughter line, where the pigs are held in pens for 1-2 hours to ensure calmness and therefore higher meat quality. The pigs are herded to where they are stunned with CO_2 followed by “sticking” and exsanguination where blood is removed (approx. 3l/pig) and collected. The carcasses then go through vertical steam scalding and a dehairer which removes most of the bristle. Hide treatment continues through a singeing oven followed by a whipping process which removes the final bristles.

Entering the “Clean slaughtering line” the animal is first opened to remove the intestines and plucks. The head and front feet are removed, and the body is divided into two equal halves which can be handled later in the slaughter line. The actual slaughter process takes less than 10 minutes and is highly automated (it takes about 50 minutes from when the pig is stuck until it exits the slaughter lines).

In the next stage the carcases are chilled to 5°C. The hanging carcase halves enter a chilling tunnel where cold air at about -16°C is blown around them. Because of the extreme cooling, the external surface of the carcase freezes while the inside remains warm. It takes 110 minutes to pass through the chilling tunnel and the carcases are then carried to the equalisation rooms where the temperature is about 5°C. There they hang for at least 16 hours, so that the temperature equalises at approx. 5°C throughout the carcass.

After chilling comes the cutting stage, when the carcasses are cut into smaller, manageable pieces. These are then loaded onto appropriate, mainly automated equipment (such as conveyer belts) which allows for transport of the pieces (hams, front parts, streaky bacon, loin) towards automated hanging equipment (so called “Christmas trees”) which takes them for further processing in the deboning facility.

There, the employees are working to satisfy various customer demands (e.g. roast pork with or without bones and boneless bacon). Trims from this process may end up in other edible processed products, for example as ingredients in salamis and minced meat.

The total consumption of inputs per pig and its distribution between meat processing stages is given in Table 4 and visualised in Figure 5 and is based on primary data from Danish Crown and DMRI (see also Appendix 8.7. Since Danish Crown are among the largest Danish producers and exporters of Danish pork, the data represents the best available and is representative of industrial practices in Denmark. Note that the same as in the farming, no differences are considered between the different genders and breeding experience of the pigs brought to the slaughterhouse.

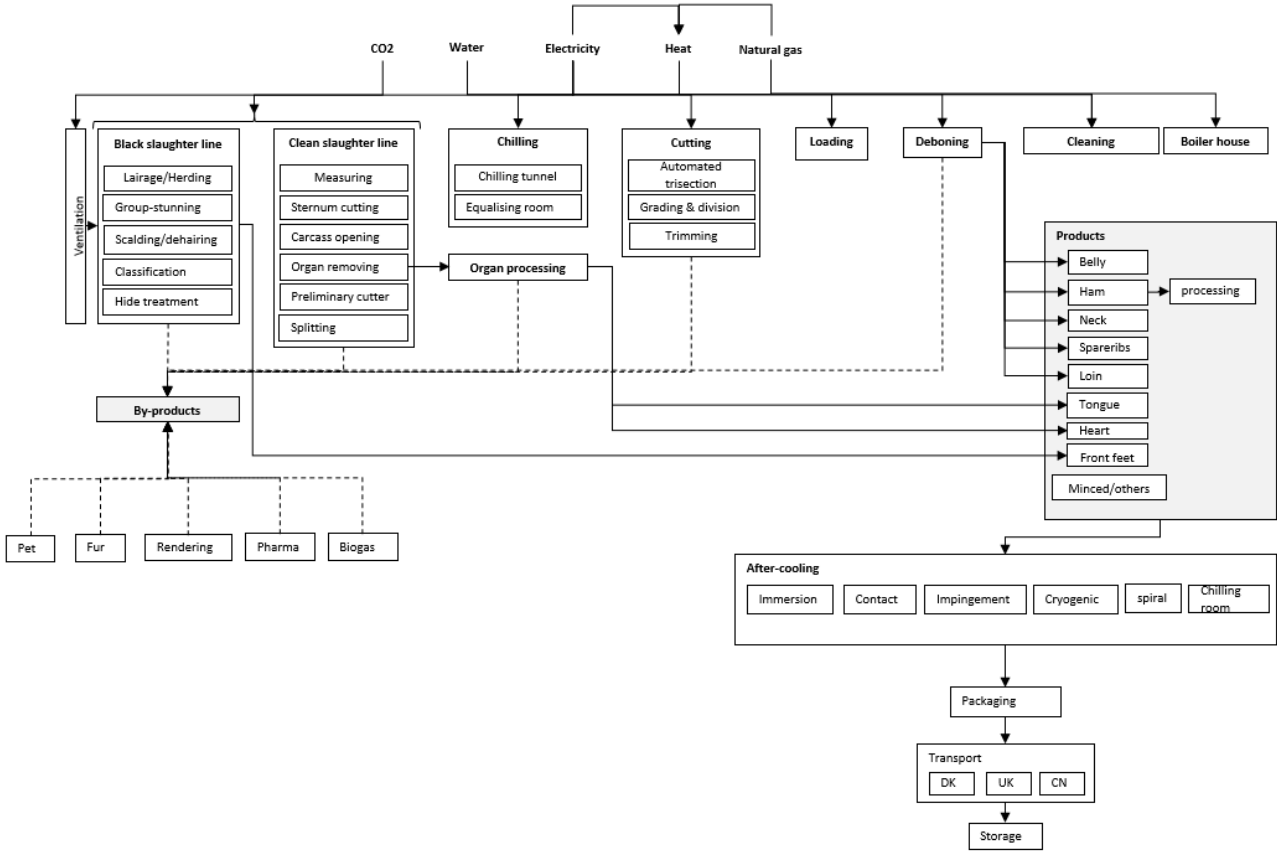


Figure 5. Product system from the slaughterhouse up to the retail market

Table 4. Resource and energy consumption per pig (live weight) and distribution per process

	Electricity (kWh)	Water (l)	Natural gas (Nm3)	Liquid CO2* (kg)
/pig (live weight)	13.67	197	1.40	0.56
Washing area		7.52%	1%	
Black slaughter line	20%	25.7%	23%	50%
Clean slaughter line		24.36%		
Organ processing/by-product production	6%	9.65%		
Chilling	40%			
Cutting	5%	4.61%		
Deboning	10%			
Cleaning	14%	16.61%		
Boiler (process and space heating)			71%	
Ventilation	2%			
Evaporative cooling		3.5%		
Others	3%	8.04%		
Smoking oven			4%	
Energy recovery	0.83 kWh		0.58 kWh	

*The remaining 50% is used for generic cooling purposes

Data for the wastewater emissions from slaughterhouse are taken from FAO data based on processing plants in the Netherlands (Verheijen et al. 1996). These data indicate that 2.4 kg BOD and 0.6 kg Nkj (Kjeldahl nitrogen) per tonne carcass enter the wastewater system. Table 5 gives the corresponding values per 86kg animal carcass.

Table 5. Quality of the wastewater in the slaughterhouse

Waste water emissions from slaughterhouse	Per carcass (86 kg)
BOD	0.21 kg
Nkj	0.05 kg

3.2.1 Slaughterhouse outputs

The outputs from the slaughterhouse include the assessed cuts and secondary products. These can further be distinguished in 1) co-products for human consumption; 2) edible by-products used as animal feed; 3) non edible by-products used for industrial applications. The EU commission in the report "Best Available Techniques in the Slaughterhouses and Animal By-products Industries" provides a simplified diagram (in Figure 6) to represent all the alterative downstream processing and by-products from pig slaughtering (EC 2005). The slaughterhouse outputs and their corresponding uses are given in Table 6.

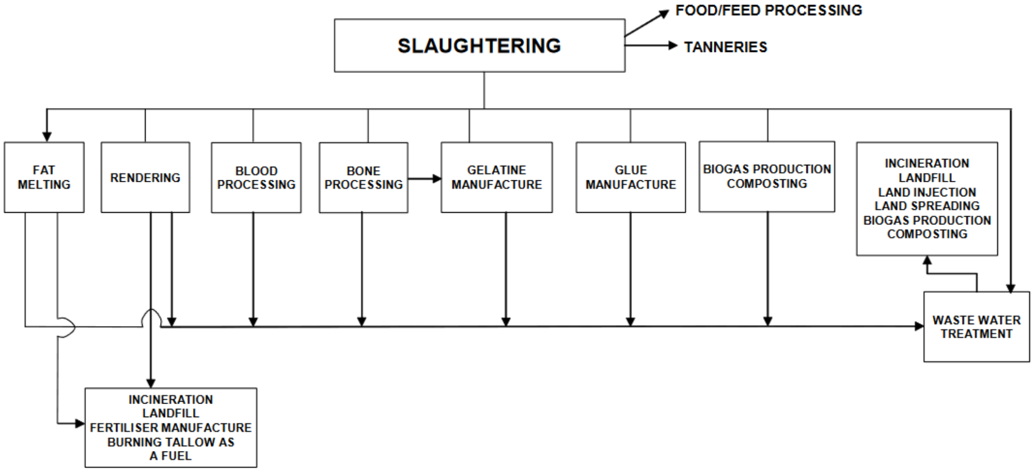


Figure 6 Typical outputs from slaughterhouse

Table 6. Slaughterhouse outputs and intended use (Thy 2016)

kg/ tonne pig carcass	Human	Pet	Fur	Rendering	Pharma	Biogas
Muscle	640	0	0	0	0	0
Bone	114	0	2	16	0	0
Fat	52	6	1	0	0	16
Blood	12	10	11	0	0	0
Liver, heart,	11	11	4	0	0	0
Other byproducts	11	10	6	4	0	0
intestines	1	6	5	1	2	4
destruction	0	0	3	51	0	0
	840	**43**	**32**	**72**	**2**	**20**

Following the recommendation of PEFPCR, the allocation of the impacts to the different slaughterhouse outputs is done on the basis of weight. Therefore, the total impact up until this life cycle stage is to be distributed on the basis of the ratios given in Table 7. The table shows the weight of the products under assessment (~41%of live weight), other edible products for human consumption (~48%) and other by-products (~15%) using the assumptions documented in Table 6.

The products under assessment not only have different compositions (given in Table 12) but also go through different processing in the slaughterhouse as seen in Figure 5. For instance, considering only the parts under study, the front legs are removed in the black slaughter line; the heart is removed in the separate line that processes the organs while the loin is the output of cutting and deboning processes. Additionally, some of the products will go for further processing into cold cuts. There is therefore a need to relate the impacts from the different slaughtering processes to the relevant products. Table 7 shows how this is done via mass based allocation. The table also clarifies the pig weight processed in each step.

Table 7. Mass based allocation factors for distributing the impacts from each slaughterhouse process to the corresponding outputs

	Processed animal	Loin	Neckbone	Ribs	Feet	Tongue	Ham	Belly	Heart	Minced meat	Others edible	Others inedible
	Product weight[1]->	1.28	1.19	0.57	0.84	0.24	15.74	7.87	0.32	6	47.2	15.48
	Animal weight	**% allocation based on each cut's contribution to the animal-weight going through each process**										
-Farming -Transport from farm -Washing area -Black slaughter line -Clean slaughter line -Cleaning -Heating -Ventilation -Evaporative cooling -Others -Energy recovery -wastewater	**104**	1.2%	1.1%	0.6%	0.8%	0.2%	15.1%	7.6%	0.3%	5.8%	45.4%	14.9%
Organ processing/ byproduct production[2]	**29.1**					0.8%			1.1%	7.7%[3]	60.9%[3]	20.0%[3]
-Chilling[2] -Cutting -Deboning	**74.9**	1.7%	1.6%	0.8%			21.0%	10.5%		5.1%[3]	40.0%[3]	13.1%[3]

[1] *The products add up to 98.4 kg which is the animal live weight (104 kg) minus 7% due to evaporative losses*

[2] *Hanging weight is assumed to be 72% of live weight* (ODA 2016)*. This means that 76.2 kg will proceed for chilling/cutting/deboning. The rest (29.6 kg) is assumed to go for 'Organ processing /byproduct production'.*

[3] *For some of the slaughtering processes weight allocation is straightforward e.g. from the 29.6 kg of 'organs', it is clear that 0.64 kg are 'heart' and 'tongue' so weight allocation is accurate (weight allocation: 0.63/29.6=2.2% of the impact should be allocated to these products). The rest 97.8% of the impact is allocated among the more unclear products ('minced meat and 'others) based on their weight.*

1) Co-products for human consumption

These are edible products other than the assessed products. The popularity of certain parts of the pig and the different products varies across markets. What is regarded as a speciality in China is possibly considered waste in Denmark and vice versa. An example of more specialised products is that 10,000,000 Danish pigs' ears, 20,000,000 trotters and 5,000,000 pigs' brains are exported from the Danish Crown Pork plant location at Horsens, Jutland, Denmark to China each year (DC 2016b). The export of different parts depends on local diets and resulting consumer demand for different products (see Appendix 8.1).

2) By products for non human consumption (feed and industrial uses)

The downstream uses for the by-products are summarised in the following paragraphs. Further details related to the environmental impacts for each of them can be found in literature (EC 2005). However it is beyond the scope of this assessment to analyse them further.

Rendering is a process that heats the material, separates the fat (tallow) from the solids (meal) and then further processes the meal and tallow depending on feed material quality and market requirements. Rendering can be done at high or low temperature and depending on the process used, various types of meal can be produced (meat meal, bone meal or, more commonly meat-and-bone meal). The attained products can be used in applications ranging from edible products to industrial ones. As already discussed bone meal can be used as pet food or as fertiliser. The organic load in the wastewater stream from rendering is used as an input to the biogas production process. Figure 7 gives an impression of all the resources consumed and coproducts produced from the rendering process. Blood is normally processed separately as it has a higher value, as discussed in the following paragraph.

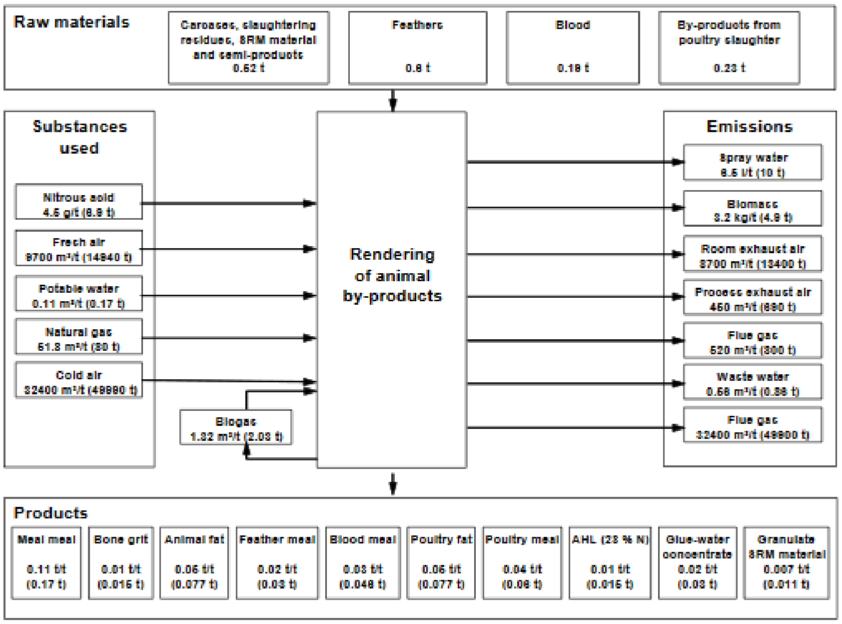


Figure 7 consumption and emission for an example rendering plant (EC 2005)

Animal feed: Instead of being directed to rendering, blood, intestines, other internal organs, fat and other by-products may be used for animal feed e.g. used for pet animals. The main content is blood which is collected in the black slaughter line. For its use as feed, blood is typically dried and the resulting blood meal can be handled more easily. Blood meal contains mostly protein and is used to supplement animal diets based on cereal grains, plant by-products and forages as it has been shown to be a satisfactory replacement for other protein sources. Other products derived from blood include fresh blood, haemoglobin and plasma.

Pharma industry: The collagen extracted from skin, bones and connective tissues goes through a partial hydrolysis process, where the natural molecular bonds between individual collagen strands are broken down into a form that rearranges more easily. The end product is gelatin, a mixture of peptides and proteins.

Biogas production: By-products directed to biogas production consist primarily of slurry from the stables at the slaughterhouse, contents of casings and stomach, sawdust from lorry transport of the pigs (DC) and wastewater from various processes. The materials are digested anaerobically to produce biogas, the methane proportion of which can then be used to produce heat and electricity. The treated solids separated from the liquid in the digestate from the anaerobic digestion process can be returned to agriculture and applied to crops as fertilizer. The use of such compost is subject to the restrictions specified in ABP Regulation 1774/2002/EC. Energy. For each unit of electricity generated from biogas, 1.5 units of heat may be produced as hot water at over 80 ºC. The derived fuel from the fat has a calorific value 36-39.8 MJ/kg and it substitutes the corresponding amount of typical heat.

3.2.2 System expansion and product substitution

Food product substitution choices are uncertain since there is no universally agreed causal link between each product and its substitute. For example - what is the alternative of pork feed? It could be a beef derived feed, any other meat product or maybe a vegetable based alternative. Therefore, deciding on the substitution options does not have a strictly scientific basis, but is rather based on value choices so there are consequently several approaches available. For example Wiedemann and Yan (2014) substitute animal protein meals with vegetable alternatives such as soybean meal and cereal grain, to provide an equivalent level of energy and protein as the animal protein meal.

In the present study, we have assumed that pork by-products can be used as substitutes for average similar products in the market, in accordance with the requirements of the ILCD guideline (EC-JRC 2010). Edible feed (pork blood and bone meal) would be used as a substitute for the corresponding meal from the “average animal” in the market, which we have assumed is bovine (46%), poultry (1%) and sheep (53%). The split between the different products is based on slaughtered livestock weights provided by Eurostat for DK in 2014 which are seen in Table 8 (Eurostat 2014).

Table 8. Average meat composition (based on total animals slaughtered in Denmark in 2014) (Eurostat 2014))

Animal	Total slaughterings (1000 tonnes)	Average animal (excluding pigs)
Pigs	1587	
Bovine	126	46%
Poultry	2	1%
Sheep	143	53%

Regarding the impacts from the average meat, the ecoinvent v3.1 database provides generic LCIs for the alternative meat products and their co-products. We have used a mass based allocation key to derive the impacts of the specific substituted functions and this key is assumed to be same as for pork (shown in Table 6): edible cuts for humans (84%), feed (7.5%), rendering (7.2%), pharma (0.2%) biogas (2%). For the biogas, there is an established biophysical causal link between fat and substituted heat relating to the calorific value of the fat, so this has been used as an allocation key to substitute typical heat use in that market. The assumptions related to avoided production are given in Table 9.

Table 9: allocations keys for substituting 'average meat' by-products

Secondary functions (% live weight)	Allocation factors for assigning impacts to the corresponding functions of the average meat		
	Bovine (46%)	**Sheep (53%)**	**Poultry (1%)**
Feed (7.5%)	3.5%	4.0%	0.1%
Pharma (0.2%)	0.1%	0.1%	0.00%
Rendering (7.2%)	3.3%	3.8%	0.1%
Fat for biogas (2%)	Substitutes natural gas. Assumed heating values for fat: 38MJ/kg. For natural gas 49 MJ/kg. 1 kg of fat corresponds to 0.78 kg natural gas		

3.3 Post slaughterhouse processes (curing, cooking)

It has been assumed that 7-8 kg of whole ham, are used for the production of processed ham (Nersting 2016). For attaining this, the raw meat first goes through curing where a brine solution is injected directly into the muscle tissue. The brine weight is 30% of the final product weight (i.e. 2.25 kg) and has the composition given in Table 10 (Nersting 2016).

Table 10 Brine composition based on DMRI data (Nersting 2016)

	% wt
Water	80.28%
Sodium chloride	5.63%
Sodium nitrite	3.9%
Dextrose	8.7%
Sodium ascorbate	0.2%

The cured meat is then cooked at a default temperature of 75 °C (measured in the core of the meat product) based on industry practice (Nersting 2016). After cooking the core temperature needs to drop to 40 degrees in the oven via cold water and ventilation through the use of the "spray chilling process". Spray chilling involves cooled water at 2-3 °C being sprayed for 30-90 seconds at 15-30 minute intervals onto the product (Sofos 2005). In total it is estimated that there is a 10% losses in weight due to this post cooking -cooling process (Nersting 2016). After the product has cooled down to 40 °C it is then put in a chilling room to reduce the temperature to 5 °C, which is consistent with the temperature of all the other cuts in the slaughterhouse.

3.3.1 Alternative processing options

The temperature during cooking is a factor which affects the final product quality. In the context of the GlobalMeat project, alternative cooking temperatures of 70 and 65 °C have been tried. The cooking tests have been conducted in conditions similar to industrial production using 96 kg of ham (Nersting 2016). The investigation concluded that cooking temperature affects the processing energy consumption, weight losses and output quality.

a) Energy consumption: The required time for heating during processing, including holding time to reach 40 °C after cooking, could be reduced by about 30 minutes when cooking occurs at 65 °C instead of 75 °C. The corresponding energy requirements would also drop: Based on DRMI data (see also Appendix 8.7) the energy requirement for the cooking oven is 4% of the total natural gas consumption in the slaughterhouse (the total NG consumption for cooking for a year is 1.4 Nm^3). It is assumed for this energy requirement corresponds to a cooking temperature of 75 °C. Given that the heating capacity of the meat and the heat transfer coefficient of the system remain constant when the cooking is occurring in the same oven, the energy requirement and work performed is reduced in direct proportion to the temperature reduction. So cooking at 65 °C instead of 75 °C would reduce the energy requirement from 0.056 Nm^3 to 0.049 Nm^3 for 96 kg of ham cooked (capacity of the oven (Nersting 2016)).

b) Product losses: lowering the temperature from 75 °C to 65 °C leads to a decrease in weight loss from 7.6% to 5.4%. This weight loss is calculated as the difference between the raw meat entering the cooking cabins and the final weight of the cooked ham once it’s temperature has dropped to 40 °C.

c) Quality: Cooking at the lower temperature resulted in lower levels of variation in losses between the different test runs which implies a more homogeneous product and more standardised quality and increased slice yields. The better quality of the product cooked at 65 °C compared to the product cooked at 75 °C was verified by an accredited sensory panel. The products at 75 °C were found to be visually paler, more uneven in colour and drier with a more fibrous soft texture. The stiffer and more crumbly product translates into higher losses during the slicing process, therefore at 75 °C a 10% loss is expected in slicing while at 65 °C the slicing losses drop to 5%. These slicing losses are not considered a wasted product since they are integrated in other processes products such as sausages. However, this implies a downgrade from a high to a lower quality product. Table 11 summarises the cooking options. Note that cooking temperature was not found to affect the shelf life of the product

Table 11. Energy requirements (Scheller Andersen) and losses per km ham processed in 75 °C or 65°C (Nersting 2016)

°C	Natural gas (Nm3)/kg ham processed	Cooking losses (%wt cooked)	Cooling losses (%wt cooled)	Post cooling slicing losses (% wt sliced)
75	0.000583	7.6%	2%	10%
65	0.000506	5.4%	2%	5%

3.4 After cooling and Super chilling

Product temperatures are reduced from 5°C (which is the target temperature in the chillers) to just above the freezing point of meat, which is approximately -1°C. There are a number of different technologies available to achieve this temperature reduction. The following sub sections discuss some of these.

3.4.1 Alternative super chilling technologies

There are four mechanisms that can be used to change the temperature of meat: conduction, convection, radiation and evaporation/condensation (James and James 2011). Six alternative superchilling technologies covering the three first of these mechanisms are investigated in this section in order to fulfil the second objective of the study. A brief note on each of the techniques is given here based on data from literature (James and James 2011) . Other methods are not investigated due to either not being commonly used or not considered promising by Danish Meat Research Institute (DMRI) (Boalth Petersen 2015).

1) Conduction: based on heat transfer by physical **contact** between products and the cooling medium without noticeable movement in the conducting medium; typically metal surfaces (plate systems) are cooled by either primary or secondary refrigerants. Due to the nature of the process, contact chilling can not be applied to irregularly shaped meat cuts such as feet.

2) Convection: movement of a cooling medium, which can be air or a fluid. Refrigerated air is typically the transfer medium, as it is economical, hygienic and relatively non-corrosive to equipment. **Air-based** systems can range from insulated rooms (batch air chilling) to tunnels or spirals with conveyors (continuous chilling) as seen in the clean line of the slaughterhouse. The cooling rate will be a function of the thickness and fat cover of the cooked product. The air temperature, air velocity and, to a limited extent, relative humidity, are the factors that can be used to control the cooling time of the meat. The advantage of air systems is their versatility; especially when there is a requirement to chill a variety of irregularly shaped products.

Immersion is another type of convection. This is made up of a tank with a cooled liquid and a means of conveying the wrapped meat through the tank. The liquid could be a mix of sodium chloride and sodium nitrate diluted in water. Note that literature suggests binary systems such as ice slurries might achieve higher rates of heat transfer than the single state liquids (Torres-de María et al. 2005). Immersion chilling is probably the least expensive option of the alternatives that Brown et al. (1988) discuss for processed meat.

Cryogenic chilling is a subset of immersion that uses cryogenic refrigerants directly. In this case Carbon dioxide(CO_2 (refrigerant R744) is the most commonly used cryogenic refrigerant in food applications (Cavallini 2004; Urieli 2016). Food grade carbon dioxide is obtained as a sub-product from a plant in Belgium (DMRI). The gas is liquefied, then put into cylinders in this liquid state for storage. At the use stage, the pressure of liquid CO_2 is reduced suddenly to atmospheric pressure, which leads to sublimation (sublimation temperature -78.5 ^{o}C and sublimation energy 573 KJ/kg). As a result the CO_2 is cooled to such an extent that it freezes and turns into a fine, powdery solid which can be converted into dry ice by using compression e.g. into pellets. Due to the high surface heat transfer coefficients between product and the cooling medium, cooling rates of cryogenic systems are substantially higher than other refrigeration systems (see also Table 23). One drawback of this system is surface freezing which can end up to product losses

3) Radiation: significant heat flow is achieved due to large temperature difference between the surface of the meat and that of surrounding surfaces. I**mpingement** chilling is in this category. It uses thousands of high-velocity (20–30 m s^{-1}) air jets to direct air at the top and bottom surfaces of the meat product. As a result the boundary layer of air that holds heat around the product is disturbed, the resulting air layer around the product is more turbulent and the heat exchange through this layer becomes much more effective, resulting in freezing speeds close to cryogenic (James and James 2011). The technology has received attention (Everington 2001; Newman 2001; Sundsten et al. 2001) though it is best suited for products with high surface area to weight ratios, e.g. hamburger patties or products with one small dimension. For processed food, when cooked meat is removed from the cooker the rate of evaporative weight loss from the hot wet surface is very high, predominantly due to the loss of water vapour. Rapid surface cooling as achieved in impingement will significantly reduce the rate of loss.

3.4.2 Heat exchange

After their production, different cuts go through a super chilling and/or cooling process, where their temperature is reduced from the slaughterhouse level (5 °C) to -1 °C fractionally above the freezing point, of approximately -2°C) (ASHARE 2006). .

The energy required to achieve this cooling is a function of the efficiency of the refrigeration system and the product cooling load, which is calculated using the heat transfer equation below (which is based on the first law of thermodynamics)

$$Q=m\ h\ \Delta T$$

Where Q is the heat transfer required (kJ), m is the mass of product (kg), h the specific heat of the product (kJ/kg.K) and ΔT the required temperature change (K). The latter is calculated to be 6K i.e. cooling the product from 5°C (temperature in the slaughterhouse (Scheller Andersen)) to -1°C (right above the freezing point).

The energy required to achieve this temperature drop depends on the specific heat of each product, which is a function of each product's composition and which varies above and below the freezing point. For each of the identified cuts, nutritional information and content (fat, protein, ash and water) are available from Danish and U.S food databases (DTU 2016; USDA 2016).Product specifications are given in Table 12 using the same weight as in Table 1.

Table 12. Product specifications of the assessed pork products. The energy and content has been based on Danish and U.S. food databases (DTU 2016; USDA 2016)

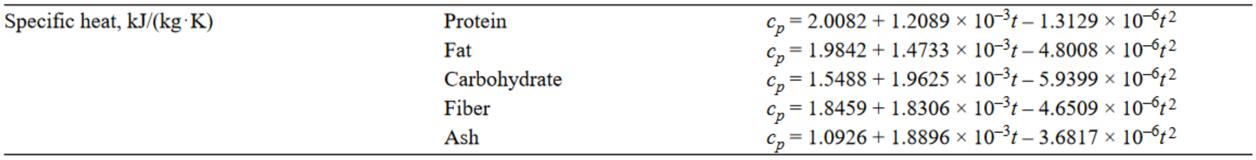
	Weight kg/pig	% live weight	kcal/100 g	Fat (%)	Protein (%)	Ash (%)	Water (%)
Tender Loin	1.28	1.2%	119	3.8	20.9	1.2	74.1
Neckbone	1.19	1.1%					
Rib bones	0.57	0.6%	275	23.4	15.67	0.69	58.43
Minced meat (5-10%)	6	5.8%	173	11.2	18.4	1	69.4
Whole ham	15.74	15.1%	165	2	20.7	0.9	60.8
Belly (for Bacon)	7.87	7.6%	518	53.01	9.34		36.74
Tongue	0.24	0.2%	225	13.27	17.00	0.94	68.30
Heart	0.32	0.3%	118	1.63	17.69	1.1	79.29
Front feet	0.84	0.8%	212	12.59	23.16	0.8	64.99

For each of the meat components the specific heat is given in Table 13. The specific heat values presented in Table 16 are calculated based on Table 14 and Table 15 (ASHARE 2006).

Table 13. Specific heat of meat components

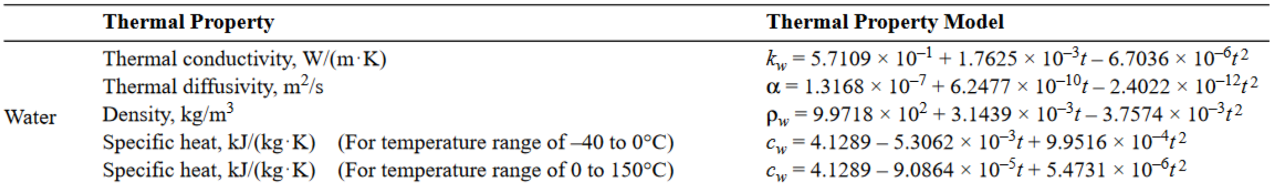
Specific heat	Fat	Protein	Ash	Water
kJ/kg K	1.99	2.02	1.10	4.13

Table 14 Formulas for calculating the specific heat of meat components



Specific heat, kJ/(kg·K)	Protein	$c_p = 2.0082 + 1.2089 \times 10^{-3}t - 1.3129 \times 10^{-6}t^2$
	Fat	$c_p = 1.9842 + 1.4733 \times 10^{-3}t - 4.8008 \times 10^{-6}t^2$
	Carbohydrate	$c_p = 1.5488 + 1.9625 \times 10^{-3}t - 5.9399 \times 10^{-6}t^2$
	Fiber	$c_p = 1.8459 + 1.8306 \times 10^{-3}t - 4.6509 \times 10^{-6}t^2$
	Ash	$c_p = 1.0926 + 1.8896 \times 10^{-3}t - 3.6817 \times 10^{-6}t^2$

Table 15. Formulas for calculating thermal properties of water



	Thermal Property		Thermal Property Model
Water	Thermal conductivity, W/(m·K)		$k_w = 5.7109 \times 10^{-1} + 1.7625 \times 10^{-3}t - 6.7036 \times 10^{-6}t^2$
	Thermal diffusivity, m^2/s		$\alpha = 1.3168 \times 10^{-7} + 6.2477 \times 10^{-10}t - 2.4022 \times 10^{-12}t^2$
	Density, kg/m^3		$\rho_w = 9.9718 \times 10^2 + 3.1439 \times 10^{-3}t - 3.7574 \times 10^{-3}t^2$
	Specific heat, kJ/(kg·K)	(For temperature range of –40 to 0°C)	$c_w = 4.1289 - 5.3062 \times 10^{-3}t + 9.9516 \times 10^{-4}t^2$
	Specific heat, kJ/(kg·K)	(For temperature range of 0 to 150°C)	$c_w = 4.1289 - 9.0864 \times 10^{-5}t + 5.4731 \times 10^{-6}t^2$

At temperatures above the initial freezing point, the specific heat of a food product can be calculated by multiplying the mass fraction by the specific heats of each components. Thus, the specific heat c_u of an unfrozen food may be determined as follows:

$$c_u = \sum c_i x_i$$

where c_i is the specific heat of the individual food components and x_i is the mass fraction of the food components (ASHARE 2006). Combining the information of Table 1 (meat components) with the information of Table 13 (specific heat of components) the specific heat of the alternative products are given in Table 16.

Table 16. Specific heat above the initial freezing point per product calculated based on the cut composition in fat, protein, ash, water, given in table 1.

	Specific heat (kJ/kg K)
Tender Loin	3.57
Neckbone	3.20
Rib bones	3.20
Minced meat (5-10%)	3.47
Whole ham	2.98
Belly (for Bacon)	2.76
Tongue	3.44
Heart	3.67
Front feet	3.41

At temperatures below the initial freezing point, the sensible heat from temperature change and the latent heat from the fusion of water must be considered. A common method to predict the apparent specific heat c_a of foods is approximated by the equation (ASHARE 2006):

$$c_a = 1.55 + 1.26x_s - \frac{(x_{wo} - x_b)L_o t_f}{t^2}$$

c_a= apparent specific heat, kJ/(kg · K)
x_s= mass fraction of solids
x_b = mass fraction of bound water
x_{wo}= mass fraction of water above initial freezing point
t_f= initial freezing point of food, °C
t= food temperature, °C
L_o= latent heat of fusion of water = 333.6 kJ/kg

The initial freezing point is assumed to be -2 °C while the end temperature of the frozen products is assumed to be -20 °C. The mass fraction of bound water may be estimated as follows:

$$x_b = 0.4x_p$$

Where xp is the mass fraction of protein in the food. The specific heat of frozen products is given in Table 17.

Table 17. Specific heat below the initial freezing point per product calculated based on the product composition in fat, protein, ash, water, given in table 1.

	Specific heat (kJ/kg K)
Tender Loin	2.97
Neckbone	2.36
Rib bones	2.36
Minced meat (5-10%)	2.58
Whole ham	2.40
Belly (for Bacon)	1.90
Tongue	2.56
Heart	2.79
Front feet	2.49

3.4.2.1 Heat transfer depending on technology type

The difference in efficiency between cooling mechanisms is represented through a coefficient of performance (COP), which is the ratio of the heat removed in the evaporator (the useful refrigeration) to the energy (electricity) put in by the compressor. A 100% efficient refrigeration process corresponds to COP of 1.

The electricity required to achieve the desired temperature decrease in the product would then be calculated by dividing the heat transfer (Q) by the COP of each cooling technology. The calculated values given in Table 18 (Scheller Andersen). The table also gives the electricity required to achieve the desired temperature drop per frozen product, using the assumption of a COP of 3.7. The values indicate that freezing requires approximately 3 times more energy compared to superchilling, which reflects the extra energy required for the latent heat of fusion of water.

Table 18. COP factors for the technologies under study and corresponding electricity requirements

	Cooling method		Freezing
	Jet-stream (Impingement NH_3)/ spiral	Cabin / immersion / contact	
COP	2.6	3.7	3.7
	electricity required (KJ/kg)		
Tender Loin	8.24	5.79	20.07
Neckbone	7.39	5.19	15.95
Rib bones	7.39	5.19	15.95
Minced meat (5-10%)	8.01	5.63	17.43
Whole ham	6.87	4.83	16.22
Belly (for Streaky Bacon)	6.37	4.48	12.84
Tongue	7.93	5.57	17.30
Heart	8.48	5.96	18.85
Front feet	7.87	5.53	16.82

For cryogenic it is assumed that the COP is 1. The energy required to cool down the different products and the corresponding CO_2 quantities is given in Table 19 and is based on the sublimation energy of R477.

Table 19 R477 consumption for cryogenic cooling of pork products

	Energy (KJ/kg)	Liquid CO2 (kg)
Tender Loin	21.42	0.037
Neckbone	19.2	0.034
Rib bones	19.2	0.034
Minced meat (5-10%)	20.82	0.036
Whole ham	17.88	0.031
Belly (for Streaky Bacon)	16.56	0.029
Tongue	20.64	0.036
Heart	22.02	0.038
Front feet	20.46	0.036

3.5 Packaging of products

Oxygen in the air hastens both the chemical breakdown and microbial decay of foods (Zhou et al. 2010). Different types of packaging have been developed to avoid such effects and to guarantee the quality of the end product for the consumer. The primary packaging options for raw chilled meat are **Vacuum packaging** (VP) and Modified **Atmosphere Packaging** (MAP). VP removes air from packaging and produces a vacuum inside. It ensures the quality (in terms of a relatively stable colour) and also allows consumers to easily view the contents (McMillin and Belcher 2012). MAP requires some or all of the oxygen in the air inside the package to be replaced with other gases such as carbon dioxide or nitrogen in order to maintain a constant package environment during storage. The majority of MAP for fresh meat has been with a high O_2 environment (around 80% O_2) that allows sufficient shelf life for processors and retailers with controlled distribution systems (Eilert 2005). Subcategories of VP and MAP (e.g. depending on the level of O2 and anoxic gases) as well as other options (e.g. air-permeable overwrap, overwrap packages in master bag and permutations of carbon monoxide (CO) incorporation) are discussed in literature (Gill and Gill 2005; Belcher 2006; Brody 2007) but will not be further discussed here. In this study a MAP environment of 70% O2 and 30% CO2 has been considered (see also Table 23).

3.5.1 Identifying packaging materials

Plastics, particularly polyolefins, are highly suitable due to their desirable properties such as ease of use in automated machines, functionality and cost (Acosta et al. 2011). Extruded films for meat packaging are summarized in Appendix 8.5 (additional details in McMillin and Belcher (2012)). VP materials for primal cuts are usually three layered co-extrusions of ethyl vinyl acetate/polyvinylidene chloride/ ethyl vinyl acetate. Low O2 vacuum packages (MAP) for retail meat cuts are usually vacuum skin packaging (VSP) systems where the retail cut is placed on a barrier styrene or polypropylene tray and vacuum sealing barrier films are then heat shrunk to conform to the shape of the product (Belcher 2006). Although an increasing choice of packaging materials is available to the MAP industry, most packs are still constructed from four basic polymers: polyvinyl chloride (PVC), polyethylene, terephthalate (PET), polypropylene (PP) and polyethylene (PE) (UNIDO 2016). Literature suggests that the plastic packaging weight for 1 kg pork product is approximately 10 g (Ingrao et al. 2015). In this study foreground data have been provided by Danish Crown, and according to these there is in average 20g of plastic materials consumed per kg of meat product. In terms of packaging material, we assume that equal proportions of HDPE, LDPE, PA, Ethylene vinyl alcohol, PET, PS and PVC are used (McMillin and Belcher 2012).For transportation, the products are put into cardboard boxes. Based on data from Danish Crown this is estimated to be 0.055 kg of cardboard/kg of meat product transported (Revsbæk 2016). Packaging materials are summarized in Table 20. Packaging details per product and country are given in Appendix 8.5.

Table 20 Types of packaging materials and quantities

Plastics	20 g/kg packed
HDPE	14.3%
LDPE	14.3%
PA	14.3%
Ethylene vinyl alcohol	14.3%
PET	14.3%
PS	14.3%
PVC	14.3%
cardboard	55 g/kg packed

3.6 Transport of products from packaging to consumer

Danish Crown exports pork products to more than 130 countries worldwide and the products exported depend on the market (see also Appendix 8.1) The magnitude of these markets shares can change over time. For example, in 2012/13 UK was the largest single market for pork in terms of revenue, followed closely by Japan and Germany. In 2014, most products were exported to China (DC 2016a). In this section the shipping to regional/global consumer markets is considered and distances and travel times are presented in Table 21. The end destinations have been selected in consultation with project partners and the aim is to identify how the distance to the market can affect the assessment results.

The distances on land within each country are assumed to be the same in all countries and equal to the distance between Horsens and Copenhagen (googlemaps 2016). To estimate the road transport from Denmark to Europe, a distance of 1500 km is assumed which is the distance from Denmark to Hungary. For the transport to markets overseas, first road transport from Horsens to Aarhus port is included (52km). Alternative sea routes are estimated from Aarhus (DMRI data) to the major port of each country and the shortest distance was selected as the reference scenario based on optimisation of logistics. Table 21 shows the distances and the corresponding travel times assuming a boat speed of 23 knots (which is considered average normal speed for cargo ships) (Notteboom and Cariou 2009; sea-distances.org 2016; worldshipping.org 2016). Based on Table 21 it is assumed that Australia, China and Japan are equivalent in terms of transport distance and time. Thus China, has been considered to be representative of all three.

Table 21 Distances and travel times to different markets

	Distance by truck (km)	Distance by boat (km)	Time by ship (days)
Denmark	267	-	-
England	52+267	606	1
Japan	52+267	11704-17264	21-31
Australia	52+267	11638-13888	21-25
China	52+267	11052-17773	20-32

All alternative 9 pork products, 6 superchilling technologies and 3 retail markets have been evaluated. However not all scenarios represent reality. Table 22 indicates which of the products are currently sold in each market. Note that the only product that is currently super-chilled is loin and it is only sold in Australia.

Table 22 Products sold per market (Revsbæk 2016)

	Loin	Neckbone	Ribs	Feet	Tongue	Ham	Heart	Minced meat
Denmark	x					x	x	x
UK	X					x		
China		x	x	x	x		x	

3.6.1 Energy for storage during transport

It is assumed that during transport, the temperature is maintained at -1 ºC and that cooling during transport is based on liquid CO_2 (573 kj/kg). Based on data from DMRI given on Table 23 for transport to Japan (Scheller Andersen), it is estimated that there is a need for approximately 0.16 kg CO_2/kg-product for the fresh products and 0.23 kg CO_2/kg-product for the frozen ones.

Table 23 Energy consumption during transport to Japan (Scheller Andersen)

Transport time	24.5	days
Container load	22000	kg
Energy consumption		
Fresh	22.6	kWh/day
Frozen	34.2	kWh/day

Upon arrival to the different countries the products are transported to the retailers where they are also stored at that temperature. The different stages in transport from cold storage to the retail outlet and then to the consumer’s refrigerator are critical control points for ensuring the overall quality and safety of the meat for human consumption. A significant factor is the temperature inside the transport vehicles and the fluctuations that occur during transport. It is a assumed that all vehicles are equipped with refrigerated systems operating constantly during transportation, thus ensuring that the product temperature is kept beneath the required maximum temperature threshold. It is assumed that there is no heat infiltration which causes the product temperature to exceed the minimum required threshold (e.g. during to weather sunny conditions, inadequate insulation and air leakage). Note that a benefit of using super-chilling seem to be that pork meat cuts keep their core temperature below 0 ºC from 12 hours to a couple of days even if the air temperature rises by several degrees. The cooling potential present in the ice on the surface of the product, namely the relatively large heat absorbed by the latent heat of evaporation of the water bound in the product, allows to maintain high quality during transport even if the cooling facilities are not working properly or other logistic problems occur in the supply chain (Nordtvedt et al. 2008).

One of the weakest links in the transport distribution chain is the period of time from when the product is purchased in the retail outlet until the consumer puts the product into their domestic refrigerator. There is only limited published data available which quantifies this parameter. The results of a consumer survey conducted in Greece indicated that about one third of the respondents need more than 20 min to transport food from the purchase point to their home, with 5% of survey respondents exceeding 45 minutes. Considering usual temperatures during summer months in Greece at above 32 °C, this duration of transport of product from retailer to domestic refrigerator may lead to a significant temperature increase in the product, with consequential adverse impacts on product quality and safety. (Koutsoumanis 2005). In this study this has not been accounted for.

3.7 Product to consumer

This section discusses how the storage temperature and the storage duration affects the products' shelf life and losses.

3.7.1 Shelf life

The shelf life model is a tool developed by DMRI to predict the shelf life of fresh meat (DMRI 2016). The model is based on storage trials performed in controlled conditions with meat from different commercial plants in several European countries, including Denmark, Sweden, Norway and Germany. Each individual storage trial included as much natural variation as possible: different producers, different processes and different products. The results of the shelf life models are given in Appendix 8.2. Results are also given for conventional cooling at 3.5 °C. The model does not currently include freezing.

Table 24 Shelf life estimation for different cuts and storage temperatures

	Pork cuts	Minced pork	Bacon
	Shelf life of fresh pork cuts - Vacuum packed and/or MAP-packed (70% O_2 + 30% CO_2) and/or stored under aerobic conditions (on "Christmas trees" (multiple hooks), in boxes, wrapped, etc.)	MAP-packed (70% O_2 + 30% CO_2)	Vacuum packed, 2-5,5 % salt in aqueous (% Sodium Chloride in the water phase, w/w), With/without Ascorbate, 60-120 ppm nitrite/nitrate added, No smoke
Storage temperatures	Days with acceptable raw meat odour		
At -1 °C only	41	31	104
At -1 °C followed by 7 d. at 5 °C	22+7	17	90
At 3.5 °C	17	13	38
At 3.5 °C followed by 7 d. at 5 °C	10+7	5+7	30+7

The super chilled meat has an extended shelf life by more than a factor 2 compared to conventional cooling it thus allows for fresh meat to reach more distant markets. Comparing to other literature, Duun et al. (2008) found that super-chilling of pork roasts to – 2.0 °C improved the shelf life significantly compared to traditional chilling to +3.5 ° C. The super-chilled roasts maintained good sensory quality and low microbiological counts during the whole storage period (16 weeks), while the shelf life of chilled samples was just 14 days. For cured loin, a storage life of >56 days has been reported for storage at -3.5 (Bogh-Sorensen, L. Zeuthen 1985). Keeping roast pork legs at -1.1 has been reported to extend storage life up to 35 days (Haugland et al. 2005).

Limitation

At superchilling temperatures, most microbial activity is terminated or inhibited, the consequential main benefit of which is the prolongation of shelf-life 1.4-4 times compared to traditional chilling (Nordtvedt et al. 2008; Duun et al. 2008). The type of cooling technologies will also affect the meat quality and shelf life, however this effect is less marked than the difference in storage temperature (Huynh Nguyen et al. 2007). For instance, Carroll and Alvarado (2008) did a comparison of air and immersion chilling. They found that air chilling carcasses can increase the shelf life of retail-packaged broiler breast fillets. Brown et al. (1988) also suggest a reduced shelf-life and a darker meat colour for immersion chilled pork. On the other hand, the same study found that immersion process leads to less weight loss. Quantitative data showing how the assessed technologies affect the shelf life and weight loss of products are not yet available.

3.7.2 Weight Loss in Products

Weight losses are expected in products as a result of dripping and evaporative losses throughout the process:

1) **Evaporative losses**: from the moment of slaughter, the meat produced begins to lose weight by evaporation. Under typical commercial distribution conditions, it has been estimated that it might lose 5-7% by evaporation between slaughter and retail sale (James 2002). A conservative 7% evaporative loss has been assumed in this study

2) **Drip losses**: The potential for drip loss is an inherent characteristic of fresh meat and is dependent on several factors (breed, diet, physiological history) all of which are determined before slaughtering. After slaughter, factors include the rate of chilling, storage temperatures and chilling and thawing procedures.

- Regarding the chilling rate, the faster the cooling of the product occurs, the less the dripping. For instance Taylor and Dant (1971) compared two cooling treatments of pig carcasses. The drip loss was less in quicker cooling by approximately 2 fold. In this sense the alternative technologies can be characterized on the basis of their heat transfer coefficient which, according to Newtons law for cooling, affects the heat transfer rate as indicated in the following equation (i.e. the rate at which heat can be removed from food).

$$q = hA(t_s - t_m)$$

Where q (W) is the heat transfer rate, h is the heat transfer coefficient, t_s is the surface temperature of the food, t_m is the surrounding fluid temperature and A (m^2) is the surface area of the food through which the heat transfer occurs.

The heat transfer coefficient is a characteristic of the refrigeration system used and how the cooling medium interacts with the product being refrigerated. The alternative superchilling technologies under assessment in this report have very different heat transfer coefficients (Table 24).

Table 25. Typical heat transfer coefficients for different refrigeration systems (the higher the rate, the faster the cooling) (James and James 2011)

Surface heat transfer coefficient, h (Wm^{-2} K^{-1})	**Refrigeration systems**
8-12	Air, low velocity (0.1 to 0.5 ms-1)
16-25	Air, medium low velocity (1 to 2 ms-1)
30-40	Air, medium velocity (3 ms-1)
50-70	Air, high velocity (6 ms-1)
100	Immersion, no flow
200	Immersion, low flow
500	Immersion, high flow
400-500	Plate, direct contact
1000-1500	Cryogenic, direct immersion

- Regarding storage. Drip loss also increases with duration and temperature of chilled storage. Work by Lee et al. (2000) showed the effect of both parameters on pork. Overall when freezing the drip loss potential rises. In this sense superchilling technologies are preferable to conventional freezing. For the cases under study, the drip loss has been investigated for different pork products (for details see Appendix 8.8) (Hededal Hofer 2016). Figure 8 presents the dryp loss for each cut after approximately 15 days. The values for superchilling represent the average dryploss after using two technologies: chilling room and impingement. Quantitative data are not yet available for the rest of the technologies. Based on the product weights given in Table 1 a weighted average for the dryp loss can be calculated for superclilling: 1.6 %wt and for freezing: 2 %wt.

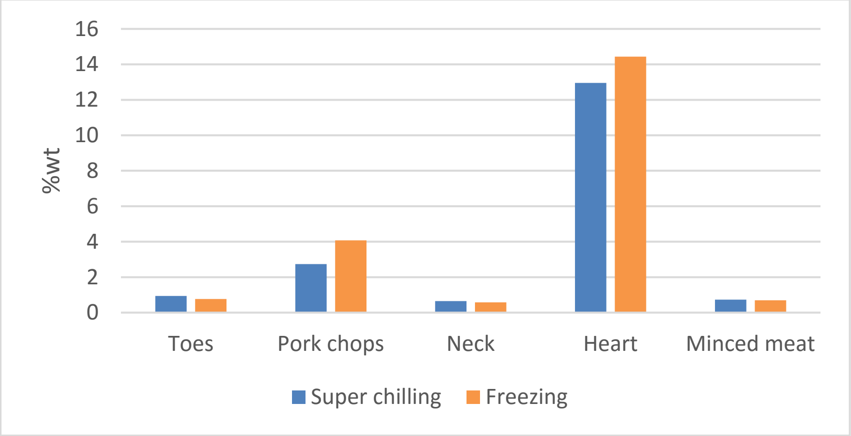


Figure 8. Comparison of impingement and chilling room (frysehus) technologies on the drip loss (Hededal Hofer 2016)

4 Impact assessment and contribution analysis

Table 26 gives the LCA results for the three impact categories of focus and for the average pork cut, i.e. average of all scenarios found in Table 34-for climate change and in Appendix 8.4- for acidification and eutrophication. To account for the 7% evaporative losses and the 1.3% drip losses the impact has been raised accordingly.

Table 26. Contribution to impact categories per kg average pork cut

		Additional impact due to losses		
	Per kg cut	Evaporative	Drip	**Total**
Climate change (kgCO$_{2eq}$/kg)	3.94	0.27	0.05	**4.27**
Acidification (molc H^{+} $_{eq}$/kg)	0.07	0.005	0.0008	**0.07**
Eutrophication (molc N $_{eq}$/kg)	0.34	0.02	0.004	**0.37**

To get an understanding of the relative contribution of the different life cycle stages, Figure 9 gives the results for 1 kg of ham, which is representative for all products. The rest of this section discusses the main findings in relation to the different a) life cycle stages; b) pork cuts; c) chilling technologies; and d) preservation and distribution to the retail markets.

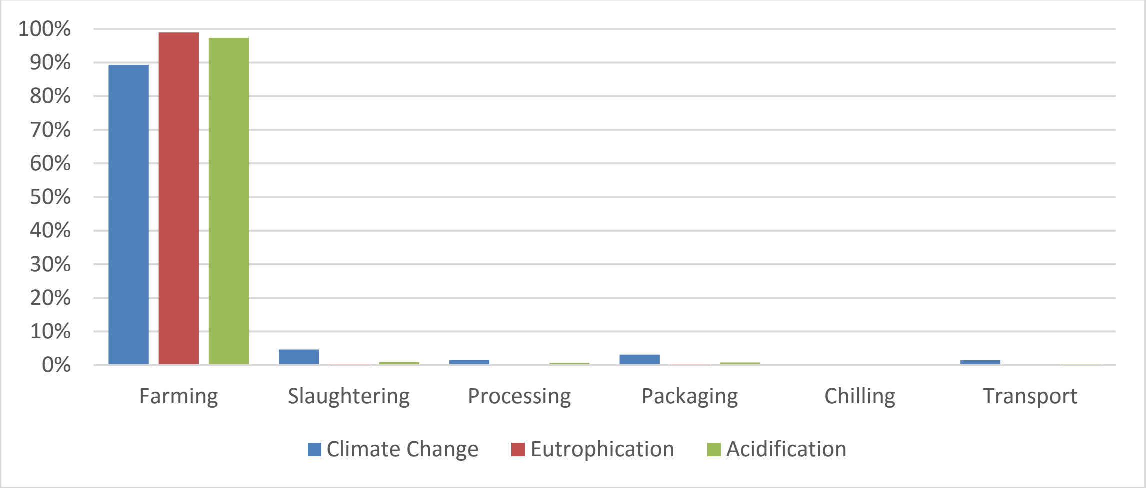


Figure 9 Relative contribution of processes across the life cycle of the product system -for ham production

Farming counts approximately 90% of the impacts in all three impact categories. It is therefore a clear hotspot and a potential area for improvement, which is consistent with other literature findings. Details on the LCA results are given in the sections bellow for the processes a) from farming to the end of the slaughtering so that the different cuts are produced; b) the post-slaughtering processes.

4.1 Farming and slaughterhouse – assessment per animal& allocation per cut

a) From farming to slaughterhouse gate the impacts from the different processes for climate change are given in Table 27 and Figure 10 per animal.

Table 27. Impacts from farming and slaughterhouse

	CC Impact (kgCO$_{2eq}$/pig slaughtered)
Farming total	**367.35**
Animal Feed	250.77
Animal feed transport	14.57
Electricity and heat	25.39
On farm emissions	70.06
Manure production	28.95
Manure application on field	-22.39

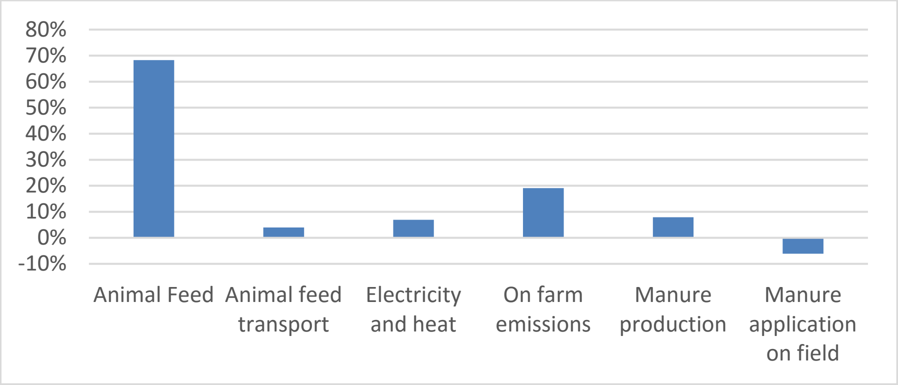


Figure 10. % contribution of the different processes to the impact from “farming”

The results for farming are dominated by the impact of animal feed. Therefore it depends on the choice of background LCI process. For instance, the generic process ‘Pigs to slaughter, pig fattening, at farm/NL’ from the Agri-footprint database (representing the processes up to the slaughterhouse) which gives 4.4 kg CO_2-eq/kg pig (agri-footprint 2015). If the later process had been chosen then the average impact per cut would be in the range of 6 instead of the 3.9 kg CO_{2eq}/kg given in Table 25.

b) For the processes within the slaughterhouse the impacts are given in Table 28.

Table 28. Impacts from slaughterhouse

	CC Impact (kgCO2eq/pig slaughtered)
Slaughtering total	**10.3**
Transport from farm	4.33
Washing area	0.04
Black slaughter line	1.82
Clean slaughter line	0.70
Organ processing/by-product production	0.42
Chilling	2.78
Cutting	0.35
Deboning	0.69
Cleaning	0.97
Boiler (process and space heating)	2.77
Ventilation	0.14
Others	0.21

The impacts from the slaughterhouse processes, are assigned to the different edible parts on the basis of mass allocation given in Table 7 and the result is given in Table 29 for all three impact categories.

Table 29. Farming and slaughtering impacts per kg edible product based on mass allocation

Impact category	Loin	Neckbone	Ribs	Feet	Tongue	Ham	Belly	Heart	Minced meat	Others edible for humans
Climate change (kgCO2eq/kg cut)	3.67	3.69	4.04	3.64	3.66	3.71	3.69	3.65	3.67	3.67
Eutrophication (molc Neq/kg cut)	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Acidification molc H+ eq/kg cut	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

Aside the edible parts, there are 15.5 kg of inedible pork parts (approx. 15% of live weight). The impacts from farming and slaughtering have also been assigned to these inedible parts on the basis of mass allocation and are given in Table 30. The table also shows the corresponding avoided production.

Table 30 Impacts from secondary services

Impact of the 15.5 kg not intended for human consumption		Avoided production	Total
Climate change (kgCO2eq/animal)	56.8	-201.82	-145.02
Eutrophication (molc Neq/animal)	5.28	-19.89	-14.62
Acidification molc H+ eq/animal	1.06	-4.62	-3.57

This total impact from the secondary service needs to be assigned to the main service (edible meat) and is distributed to the different cuts based again on mass allocation. The final result from the farming and slaughtering impact accounting for the secondary services are given in Table 31.

Table 31 Impact from farming and slaughterhouse accounting for primary and secondary services and avoided production (mass based allocation)

Impact category	Loin	Neckbone	Ribs	Feet	Tongue	Ham	Belly	Heart	Minced meat	Others edible for humans
Climate change (kgCO2eq/kg cut)	3.65	3.67	4.03	3.62	3.66	3.42	3.55	3.64	3.56	2.79
Eutrophication (molc Neq/kg cut)	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33	0.25
Acidification molc H+ eq/kg cut	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.07	0.07	0.05

Co-dependency

The results in Table 31 present the impacts per unit product (1kg). However the different products are produced together (i.e. are co-dependent). To take an example, as Table 1 showed slaughtering a pig implies the production of 1.3 kg of loins and 6 kg of minced meat. Therefore production of 1 kg of each product yields the coproduction of the rest of the products according to Table 32. The table, understandably shows that the lower the yield (kg of product/pig) the higher the total amount of pork products attained. Such information although not directly used in this study (here the LCA results are given per kg product), might be relevant to meat producers e.g. for assessing the impact of demand driven production. For instance the production of 1 kg of tongues implies the coproduction of approximately 25 kg minced meat.

Table 32 Co-production of products and contribution to climate change impact accounting for the coproduction

Loin	**Neckbone**	**Ribs**	**Feet**	**Tongue**	**Ham**	**Belly**	**Heart**	**Minced meat**	**Others edible for humans**	**Others inedible**
1.3	1.2	0.6	0.8	0.2	15.7	7.9	0.3	6.0	47.2	15.5
Co-production per kg product										
1.0	0.9	0.4	0.7	0.2	12.3	6.2	0.3	4.7	37.0	12.1
1.1	**1.0**	0.5	0.7	0.2	13.3	6.6	0.3	5.1	39.8	13.1
2.2	2.1	**1.0**	1.5	0.4	27.5	13.7	0.6	10.5	82.4	27.0
1.5	1.4	0.7	**1.0**	0.3	18.7	9.3	0.4	7.1	56.0	18.4
5.2	4.9	2.4	3.5	**1.0**	64.8	32.4	1.3	24.7	194.2	63.7
0.1	0.1	0.0	0.1	0.0	**1.0**	0.5	0.0	0.4	3.0	1.0
0.2	0.2	0.1	0.1	0.0	2.0	**1.0**	0.0	0.8	6.0	2.0
3.9	3.7	1.8	2.6	0.8	48.6	24.3	**1.0**	18.5	145.7	47.8
0.2	0.2	0.1	0.1	0.0	2.6	1.3	0.1	**1.0**	7.9	2.6

4.2 Post slaughterhouse – assessment per cut

For the post slaughtering processes, the impacts per kg cut are given in Table 33 for climate change. This part of the system is not an environmental hotspot. The impact assessment results are lower by a factor of 50 when compared to the impacts from farming and slaughtering.

Table 33 Climate change impact per kg product for the post slaughtering processes. Alternative cooling technologies and market options are shown.

kgCO2eq/kg cut		**Loin**	**Neckbone**	**Ribs**	**Feet**	**Tongue**	**Ham**	**Belly**	**Heart**	**Minced meat**
processing							0.060			
Other*	CO2 cooling	0.003	0.003	0.001	0.002	0.001	0.034	0.017	0.001	0.013
Cooling**	COP 2.6	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	COP 3.7	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Cryogenic	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.002	0.002
	Immersion	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.017
packaging	Packaging	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123	0.123
Transport	DK	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046
	UK	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069	0.069
	CN	0.258	0.258	0.258	0.258	0.258	0.258	0.258	0.258	0.258
Cooling in transport	CN	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127	0.127
	DK	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010

* cooling for generic purposes in the slaughterhouse

** COP 2.6: impingement spiral, COP 3.7: chilling room, contact, immersion

5 Scenario evaluation for different chilling options and markets

Table 34 gives the contribution to climate change, per kg product for different markets and different chilling options. Given that farming is the dominant life cycle stage in terms of impacts and is the same across all considered scenarios, the differences between the scenarios' results are insignificant. The picture for eutrophication and acidification is similar and further details are provided in Appendix 8.4. These results indicate that to maximize the environmental savings and avoid suboptimisation, farming should be the focus . This is aligned with what other literature suggests.

Table 34 Impact assessment results for all scenarios (alternative products, cooling technologies and markets)

	Climate change (kgCO2eq/kg)	Loin	Neckbone	Ribs	Feet	Tongue	Ham	Belly	Heart	Minced meat
DK	impigment and spiral	3.84	3.85	4.21	3.80	3.84	3.64	3.74	3.82	3.75
	immersion	3.85	3.87	4.23	3.82	3.86	3.65	3.76	3.84	3.77
	chilling room	3.84	3.85	4.21	3.80	3.84	3.64	3.74	3.82	3.75
	contact	3.84	x	x	x	3.84	3.64	3.74	3.82	3.75
	cryogenic	3.84	3.85	4.21	3.80	3.84	3.64	3.74	3.82	3.75
UK	impigment and spiral	3.86	3.87	4.23	3.83	3.86	3.66	3.77	3.85	3.78
	immersion	3.89	3.90	4.26	3.85	3.89	3.69	3.79	3.87	3.80
	chilling room	3.86	3.87	4.23	3.83	3.86	3.66	3.77	3.85	3.77
	contact	3.86	x	x	x	3.86	3.66	3.77	3.85	3.77
	cryogenic	3.86	3.87	4.23	3.83	3.86	3.66	3.77	3.85	3.78
CN	impigment and spiral	4.16	4.18	4.54	4.13	4.17	3.97	4.07	4.15	4.08
	immersion	4.18	4.20	4.56	4.15	4.19	3.98	4.09	4.17	4.10
	chilling room	4.16	4.18	4.54	4.13	4.17	3.97	4.07	4.15	4.08
	contact	4.16	x	x	x	4.17	3.97	4.07	4.15	4.08
	cryogenic	4.17	4.18	4.54	4.13	4.17	3.97	4.07	4.15	4.08

Focussing on the different market options, the impact of transport distances is illustrated in Figure 11 which shows the 3 scenarios considered for transporting 1 kg of meat to Denmark, the United Kingdom and China.

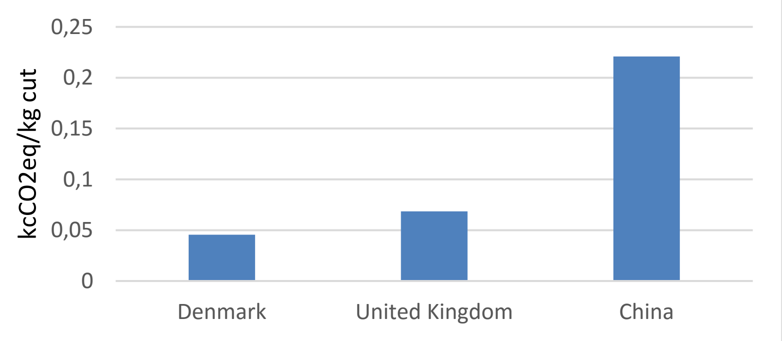


Figure 11 Impact of transport for the alternative market options for climate change (kgCO$_{2eq}$/kg) impact category

Figure 12 shows the climate change impact due to alternative aftercooling options and markets. The figure shows that superchilling is environmentally better compared to freezing in terms of energy requirement.

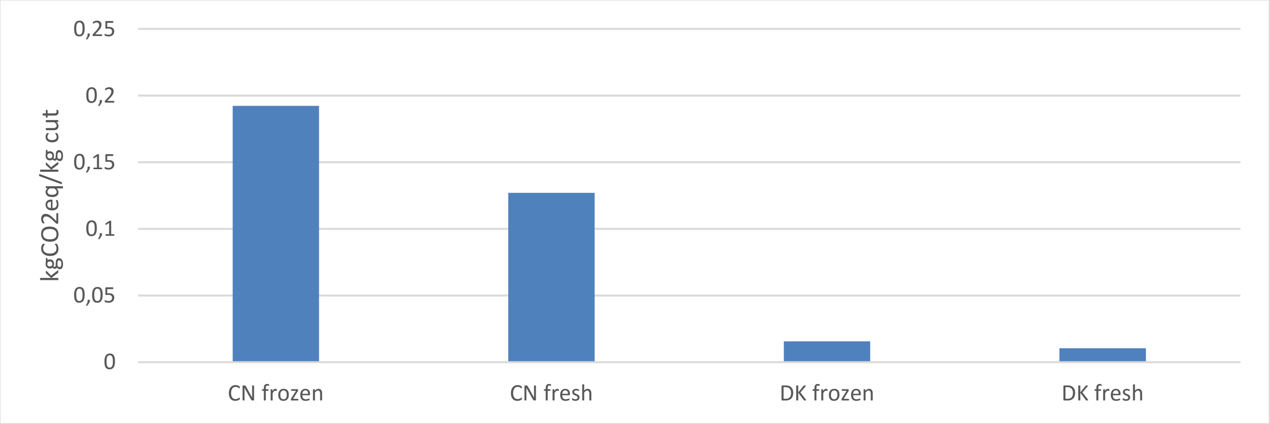


Figure 12 Climate Change impact from cooling during transport per kg cut

Further focussing on the alternative technologies the impact of super chilling varies and is illustrated in Figure 13, which shows the 6 scenarios for cooling 1 kg of processed ham. The figure also shows the impact from freezing, taking into account only the energy consumption. Super-chilling has approximately one third of the climate change impact compared to freezing. Looking at immersion, more than 95% of the impact shown in is due to the use of plastic material (which assumes that 17.7g/kg of plastic is reused 3 times).

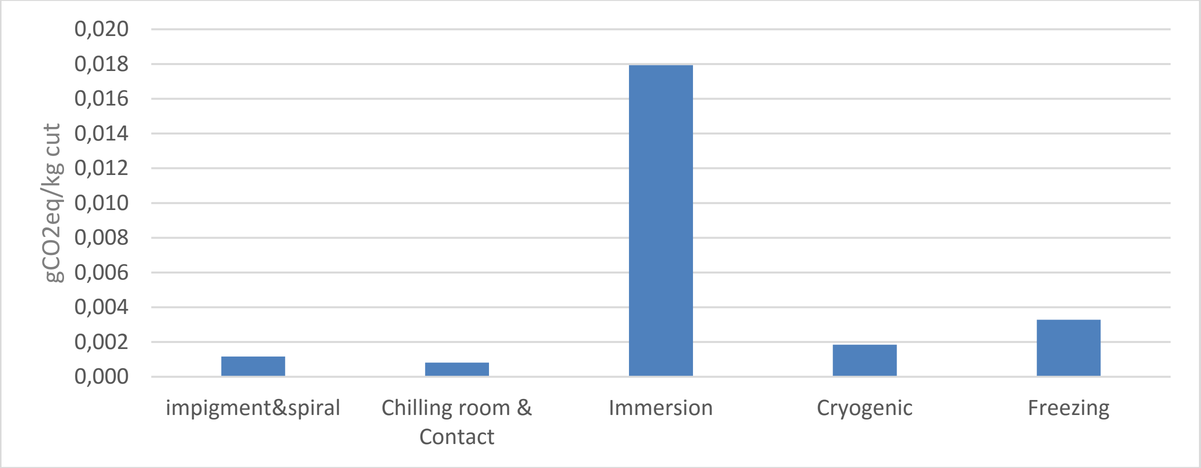


Figure 13 Impact of cooling -alternative cooling technology options for climate change impacts (kgCO_{2eq}/kg)

5.1 The effect of drip loss and shelf life

Regarding the drip loss, the technologies are characterised on a qualitative level, assuming that the faster the cooling, the lower the drip loss (Table 35 based on Table 24). A rough estimation of the drip loss was based on the quantitative data given in Figure 8 and Appendix 8.8. As mentioned in section 3.7.2 we have assumed in average 1.6% drip loss for all technologies. The drip loss is the liquid part of the product that separates from the solid and which is discarded once the packaging is opened. It therefore translates into less quantity available to the consumer (see also losses in Table 26). The drip loss will affect the final weight of product that will be cooked. However, moisture losses during cooking are typically an order of magnitude higher than drip losses during refrigeration. Consequently, the drip loss is not expected to affect the eating quality of the products.

Table 35 Qualitative rating for drip loss (the greener the better the performance)

Cryogenic	Impingement	Contact	Immersion	Air (chilling room and spiral)
🟩	🟩	🟨	🟧	🟥

Regarding shelf life, Table 36 characterizes the feasibility of the transport to the different markets. It shows that although superchilling makes it feasible for fresh meat to reach distant markets, there is only a short time window during which the products can stay with the retailer (e.g. for minced meat, the shelf life is approximately the same as the travel time).

Table 36 Shelf life for different cooling options and feasibility for travel time of 20-32 days

Storage at different temperatures	Shelf life		
	Fresh cuts	Minced meat	bacon
At -1 °C only	41	31	104
At -1 °C followed by 7 d. at 5 °C	29	17	90
At 3.5 °C	17	13	38
At 3.5 °C followed by 7 d. at 5 °C	17	12	37

Estimating the potential reduction of food waste due to the extension of shelf life remains a difficult task. The challenges are related to supply chain complexities such as long supply chains and several storage points, and more significantly, to consumer behaviour (such as shopping in larger volume resulting in longer storage periods at households). These factors imply that shelf life extension may not guarantee consumption before products have reached the “best before date ”. Additionally there is an increasing demand for “fresh products” , which may lead to the perception that products with longer shelf life are considered less fresh (Amani and Gadde 2014).

To quantify the potential impact of the shelf life extension to the reduction of food waste, a study by WRAP (Waste & Resources Action Programme) has been used (Lee and Osborn, Steve Whitehead 2015). The authors estimate that there is in total 4.2 million tonnes of avoidable food waste produced annually by UK households (food and drink thrown away that was, at some point prior to disposal, edible) and that approximately 2 million tonnes of those are disposed of because they are ‘not used in time’ . They also find that an increase in product life is more likely to impact behaviour for products that have relatively short shelf life (for example, the fresh cuts compared to the cured ones), because it gives proportionately more time for a sale or for the product to be used in the home. They estimate that an increase of just one day could help prevent 5% of avoidable food waste. Incentives can also be identified for the retailers. Retailers use on-shelf availability (OSA) as a key benchmark for products and, increasingly, their suppliers are being judged by this metric. ECR Europe reports that a 1% increase in OSA results in a 0.5% increase in sales. This demonstrates that it is in the retailer’s interest to obtain the maximum period of time in which to sell products.

6 Conclusion and relation to other literature

The present LCA study assessed the provision of pork products to the market. It took into account 9 different pork products (front feet, neck, ribs, loin, processed loin, hearts, tongues, minced meat, belly) and 5 alternative after cooling technologies. These technologies were either already used on an industrial scale (chilling rooms, spirals, impingement) or are new innovations under development (immersion, contact). The assessment was done for 3 different markets (Denmark, United Kingdom and China). The assessment of the different scenarios served two purposes:

1) **The environmental assessment of Danish pork products (Danish Landrace breed)**: The purpose is to put the pork production system into perspective and to identify the relative contribution of different life cycle stages and corresponding improvement potentials. The results showed that the impacts to climate change, acidification and eutrophication (the impact categories identified as most relevant for meat products by the draft PEFPCR) are approximately 3.9 kgCO2eq/kg, 0.07 molc H+ eq/kg and 0.34 molc N eq/kg respectively. An additional 8% of these values can be expected due to evaporative and dripping losses.

Considering climate change, the impact category most reported in literature, the results from this study are consistent with those of other researchers', where values typically range from 3.1-3.6 kg CO2-eq (Dalgaard 2007; Stephenson 2010; Nguyen et al. 2011; Reckmann 2013; Reckmann et al. 2013). In terms of hotspots, farming is the dominant environmental hotspot in the product life cycle, contributing approximately 90% to all three impact categories. Consequently, the total impact from pork is less sensitive to changes within the other life cycle stages. For instance, the transport to China has 5 times the impact compared to the transport in Denmark from a climate change perspective, yet in the whole life cycle of the product, transport accounts for less than 1% of the total impact. This lack of sensitivity also exists for the alternative cooling technologies; after-cooling only marginally affect the overall LCA results.

Aside from the transport distance, the different markets imply different shelf lives and dripping losses. Longer transport implies less availability of the products to the retailer as more of the total product life is using during the transportation stage. For instance, transport to China by ship would require 25 days of transport. The fresh products would then have 15 additional days of shelf life if stored at -1°C). If the retail temperature is 5°C and that the retailer keeps the products for a week, transport of fresh products to China is possibly not viable from a food safety perspective since the transport time (approx. 25 days) would exceed the shelf life (17-22 days).

2) **The comparative assessment of alternative after cooling technologies**: The purpose was to identify the technology providing the least environmental impacts from a life cycle perspective and to facilitate a benchmarking of these technologies relative to existing after-cooling approaches.

Super chilling performs environmentally better than freezing by a factor of 3 due to the lower energy consumption. Comparing the alternative technologies on the basis of 'cooling 1 kg of each product', the use of conventional chilling rooms and then novel technology 'contact' perform better. However, contact is less flexible since it requires that the cuts have a regular shape, for example the technology can not be used for cooling pork feet. The impact from immersion is significantly higher than the rest due to the soft plastic used to wrap the cuts prior to passing through the cooling medium. The comparison of the different technologies does not account for other decision criteria, such as costs and physical space requirements, which need to be co-evaluated in order to conclude on the most preferable option.

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8 Appendix

8.1 Meat products, coproducts and alternative markets

Figure A. Alternative coproducts from a pig

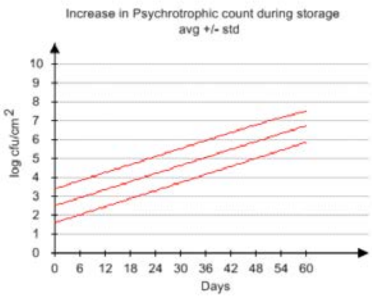
Typical export of cuts depending on local diet:

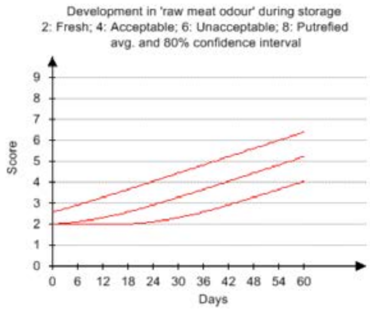
- Hearts: Russia, Eastern Europe, Germany and, to a small extent, Denmark.
- Kidneys: the Far East, France, the UK. In France, kidney pie is a real delicacy.
- Lungs: Germany. Used a lot in sausages.
- Liver: Germany, Russia, the new EU member states such as the Czech Republic and Hungary. And Denmark, where we use it for liver pâté.
- Tongue: Germany, the UK, Denmark. In the UK, tongue is normally served whole wrapped in minced meat.
- Diaphragm: Europe, the Far East. The diaphragm adds extra juice and flavour to minced meat as well as an attractive meat colour.
- Trotters: Korea, China, Russia. Tails: France, the US and Africa.
- Brain: France. Thinly sliced, fried and eaten like crisps.
- Uterus: The Far East. The uterus is often used to add juice and flavour to soups. Moreover, many people believe that eating uterus will improve a woman's fertility.
- Snout: Europe. Used throughout Europe for brawn, but can also be dried and used as animal feed.
- Ears: China.

8.2 Shelf life

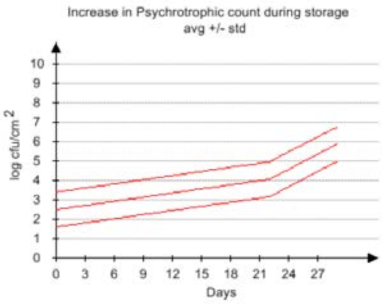
8.2.1 Fresh pork cuts

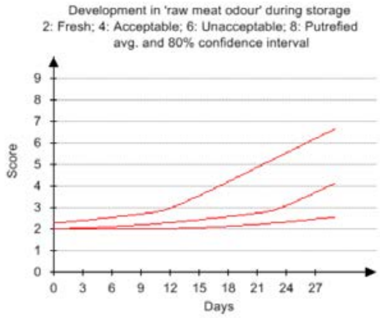
For storage at -1 ^{o}C the meat odour is acceptable for up to 41 days



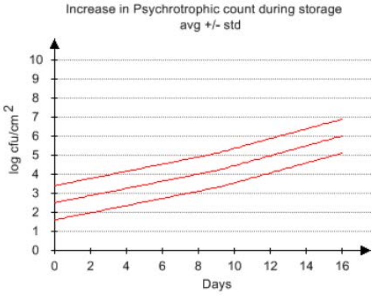


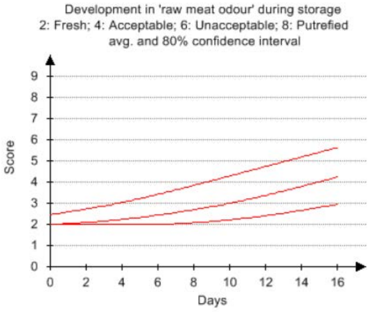
For storage at -1 ^{o}C for 22 days and then it lasts at 5 ^{o}C for 7 more days.



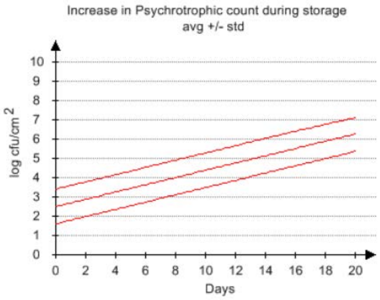


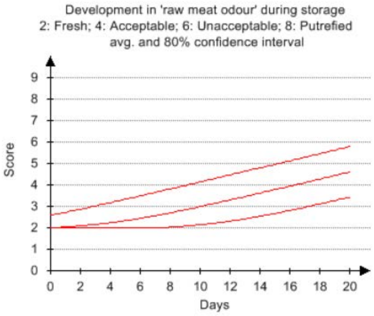
For storage 10 days at 3.5 ^{o}C and for approx. 7 days more at 5 ^{o}C





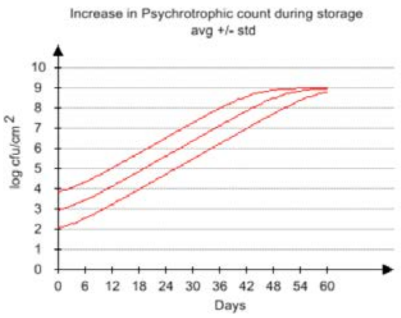
For storage at 3.5 ^{o}C for 16 days

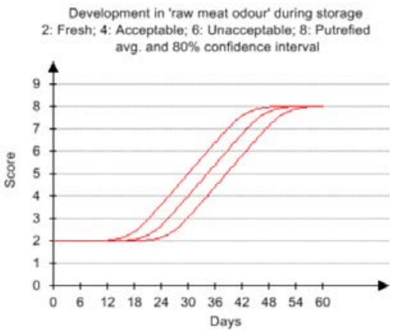




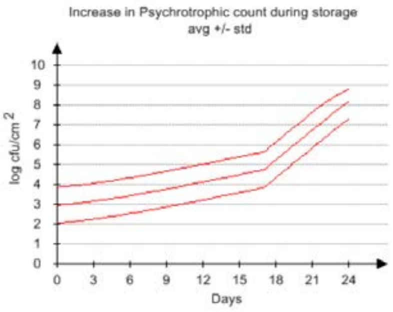
8.2.2 Minced pork

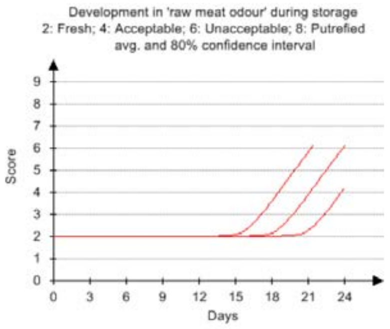
For storage at -1 °C the odour is acceptable till the 31st day



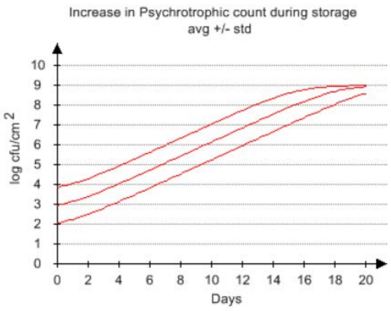


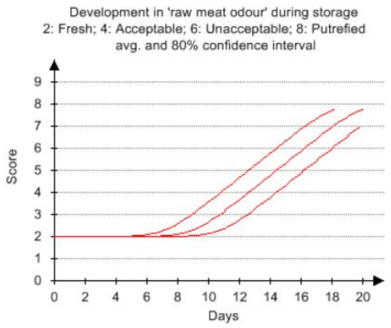
For storage at -1 °C for 17 days and then at 5 °C for approximately 7 days



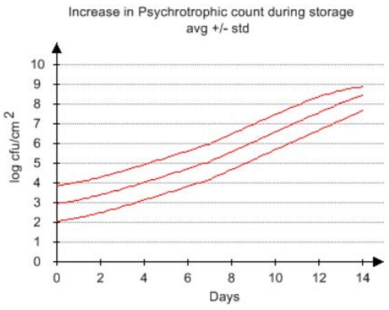


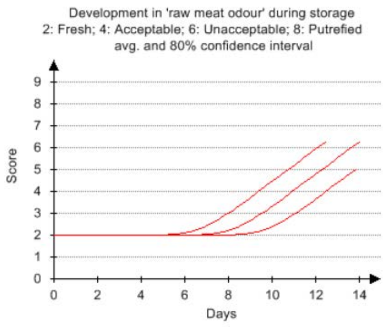
Storage at 3.5 C for 13 days





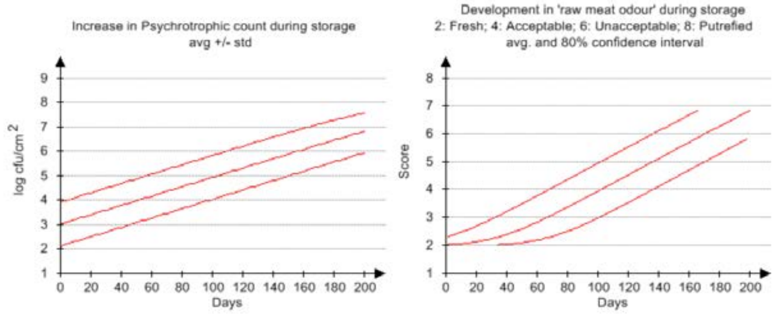
At 3.5 °C for 5 days followed by 7 days at 5 C



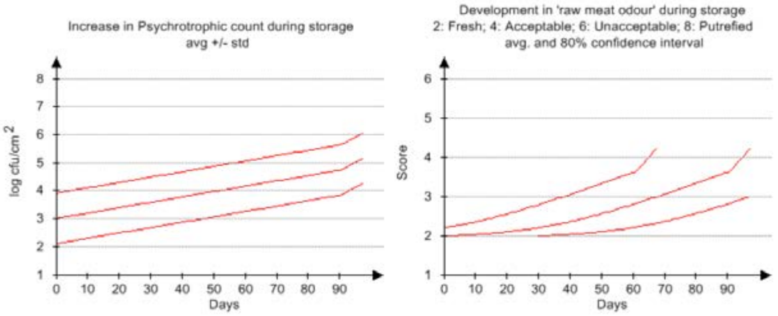


3) Bacon

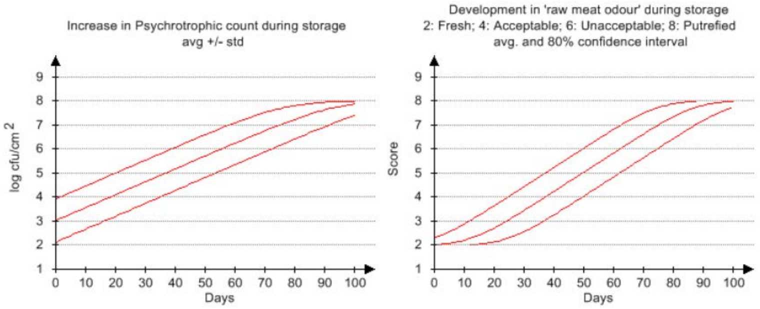
At -1 °C, the odour is acceptable till the 104th day



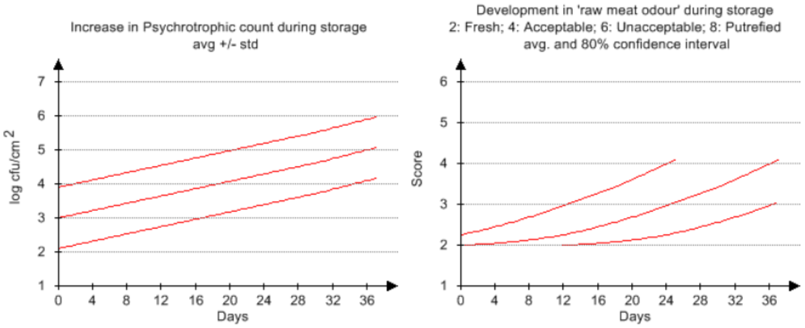
At -1 °C for 90 days then it lasts approximately 1 more week in 5 °C



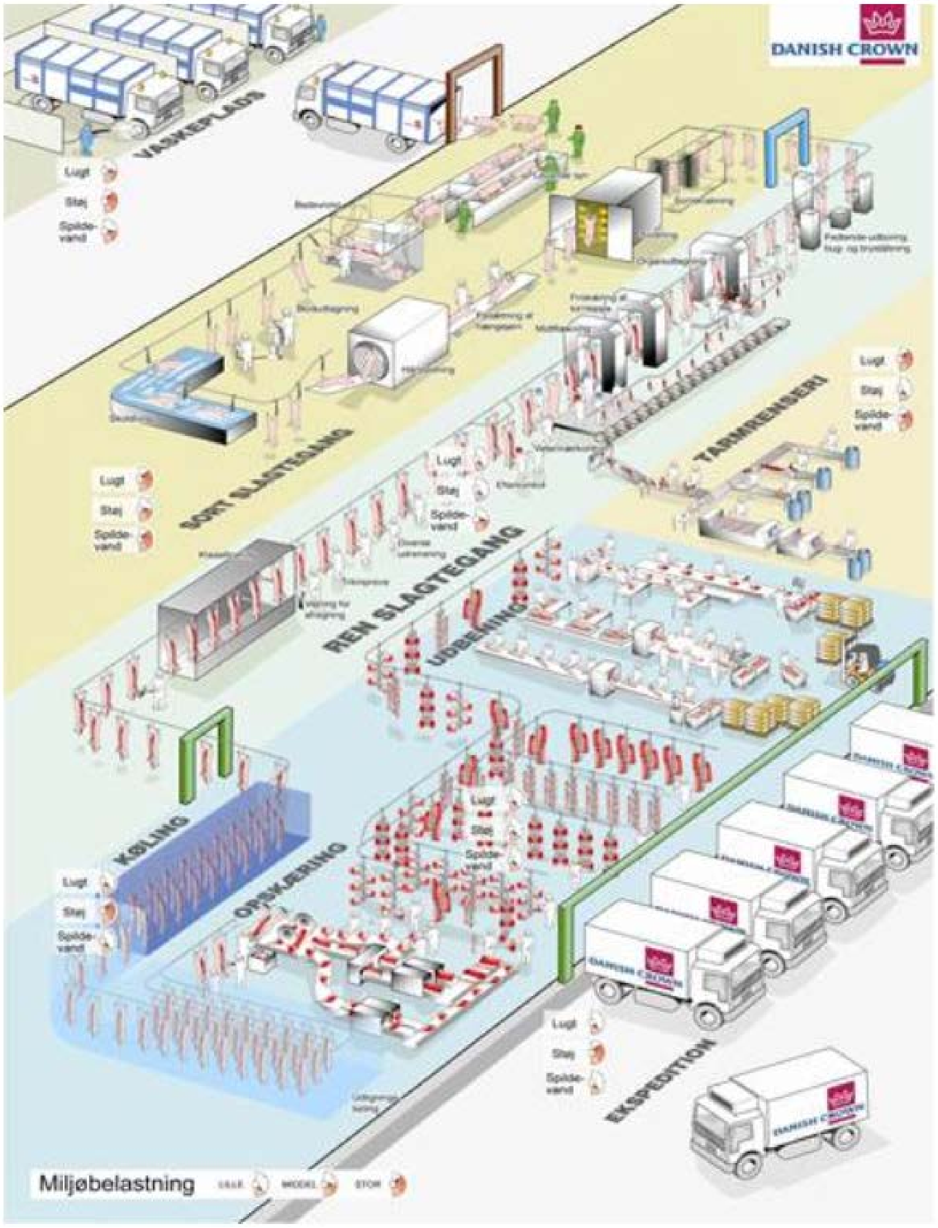
At 4 for 38 days



For 30 days at 4 and then 7 days at 5



8.3 Slaughterhouse processes



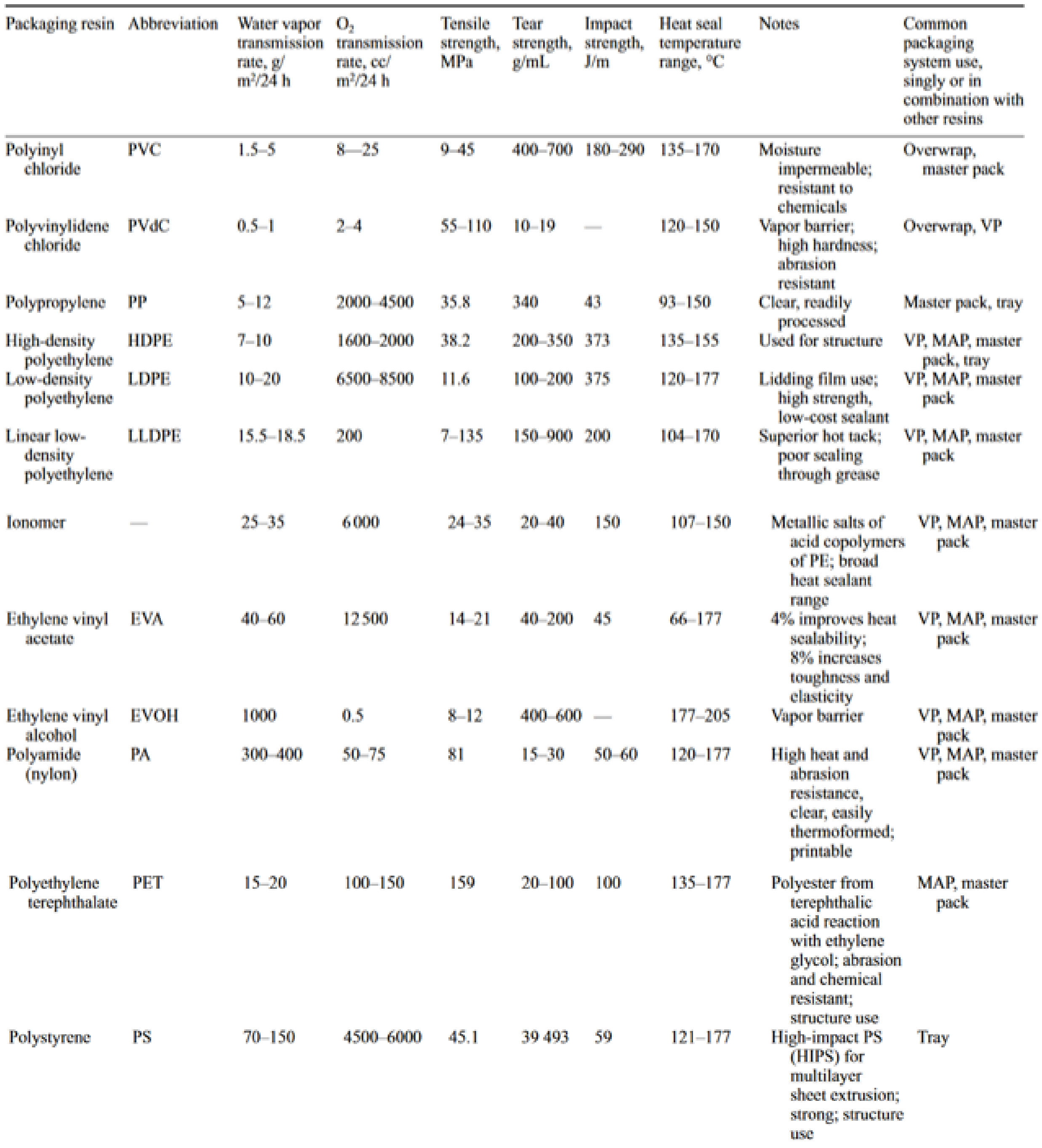
8.4 Scenario results for Acidification and Eutrophication

Eutrophication (molc N eq/kg)		Loin	Neckbone	Ribs	Feet	Tongue	Ham	Belly	Heart	Minced meat
DK	impigment and spiral	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
	immersion	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
	chilling room	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
	contact	0.34	x	x	x	0.34	0.31	0.33	0.34	0.33
	cryogenic	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
UK	impigment and spiral	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
	immersion	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
	chilling room	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
	contact	0.34	x	x	x	0.34	0.31	0.33	0.34	0.33
	cryogenic	0.34	0.34	0.34	0.34	0.34	0.31	0.33	0.34	0.33
CN	impigment and spiral	0.35	0.35	0.35	0.35	0.35	0.32	0.34	0.35	0.34
	immersion	0.35	0.35	0.35	0.35	0.35	0.32	0.34	0.35	0.34
	chilling room	0.35	0.35	0.35	0.35	0.35	0.32	0.34	0.35	0.34
	contact	0.35	x	x	x	0.35	0.32	0.34	0.35	0.34
	cryogenic	0.35	0.35	0.35	0.35	0.35	0.32	0.34	0.35	0.34

Acidification (molc H+ eq/kg)		Loin	Neckbone	Ribs	Feet	Tongue	Ham	Belly	Heart	Minced meat
DK	impigment and spiral	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
	immersion	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
	chilling room	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
	contact	0.07	x	x	x	0.07	0.06	0.07	0.07	0.07
	cryogenic	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
UK	impigment and spiral	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
	immersion	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
	chilling room	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
	contact	0.07	x	x	x	0.07	0.06	0.07	0.07	0.07
	cryogenic	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07
CN	impigment and spiral	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	immersion	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	chilling room	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	contact	0.07	x	x	x	0.07	0.07	0.07	0.07	0.07
	cryogenic	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

8.5 Packaging materials and markets

Common extruded films for meat packaging (McMillin and Belcher 2012)



Packaging resin	Abbreviation	Water vapor transmission rate, g/m²/24 h	O₂ transmission rate, cc/m²/24 h	Tensile strength, MPa	Tear strength, g/mL	Impact strength, J/m	Heat seal temperature range, °C	Notes	Common packaging system use, singly or in combination with other resins
Polyinyl chloride	PVC	1.5–5	8—25	9–45	400–700	180–290	135–170	Moisture impermeable; resistant to chemicals	Overwrap, master pack
Polyvinylidene chloride	PVdC	0.5–1	2–4	55–110	10–19	—	120–150	Vapor barrier; high hardness; abrasion resistant	Overwrap, VP
Polypropylene	PP	5–12	2000–4500	35.8	340	43	93–150	Clear, readily processed	Master pack, tray
High-density polyethylene	HDPE	7–10	1600–2000	38.2	200–350	373	135–155	Used for structure	VP, MAP, master pack, tray
Low-density polyethylene	LDPE	10–20	6500–8500	11.6	100–200	375	120–177	Lidding film use; high strength, low-cost sealant	VP, MAP, master pack
Linear low-density polyethylene	LLDPE	15.5–18.5	200	7–135	150–900	200	104–170	Superior hot tack; poor sealing through grease	VP, MAP, master pack
Ionomer	—	25–35	6000	24–35	20–40	150	107–150	Metallic salts of acid copolymers of PE; broad heat sealant range	VP, MAP, master pack
Ethylene vinyl acetate	EVA	40–60	12500	14–21	40–200	45	66–177	4% improves heat sealability; 8% increases toughness and elasticity	VP, MAP, master pack
Ethylene vinyl alcohol	EVOH	1000	0.5	8–12	400–600	—	177–205	Vapor barrier	VP, MAP, master pack
Polyamide (nylon)	PA	300–400	50–75	81	15–30	50–60	120–177	High heat and abrasion resistance, clear, easily thermoformed; printable	VP, MAP, master pack
Polyethylene terephthalate	PET	15–20	100–150	159	20–100	100	135–177	Polyester from terephthalic acid reaction with ethylene glycol; abrasion and chemical resistant; structure use	MAP, master pack
Polystyrene	PS	70–150	4500–6000	45.1	39 493	59	121–177	High-impact PS (HIPS) for multilayer sheet extrusion; strong; structure use	Tray

Markets

Plastic: average 22gr/kg product							
gr/kg	Middles	Loin	Forebone	Toes	Spareribs	Minced meat	Heart
Australia	6.515	6.515					
China			28.66667	20.66667	34.58918		
UK		6.601852		15.92593			
DK		20.10764				42.05	38.30833
Cardboard: average 55gr/kg product							
gr/kg	Middles	Loin	Forebone	Toes	Spareribs	Minced meat	Heart
Australia	41.83333	41.83333					
China			38.06667	27.53333	29.05812		
UK		66.66667		21.14815			
DK		58.19444				89.66667	139.1667

8.6 Inventory processes modelled

1_FARMING	per 1000 kg pig	
1_farming_animal feed		
Wheat grain, feed, Swiss integrated production {GLO}| market for | Alloc Def, U	1112	kg
Barley grain, feed, Swiss integrated production {GLO}| market for | Alloc Def, U	855	kg
Pig feed, fattening pigs/NL Mass	497	kg
Phosphate fertiliser, as P2O5 {GLO}| market for | Alloc Def, U	1.8	kg
Soybean meal {GLO}| market for | Alloc Def, U	341	kg
1_farming_electricity and heat		
Electricity, medium voltage {DK}| market for | Alloc Def, U	148	kWh
Heat, district or industrial, natural gas {CH}| market for heat, district or industrial, natural gas | Alloc Def, U	541	MJ
1_farming_manure use		
(burdens)		
Energy, from diesel burned in machinery/RER Energy	157	MJ
Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}| market for | Alloc Def, U	75	tkm
Nitrogen oxides	123	g
Nitrate	16.6	kg
Dinitrogen monoxide	744	g
Ammonia	8.4	kg
Phosphate	0.7	kg
(savings)		
Energy, from diesel burned in machinery/RER Energy	-11	MJ
Nitrogen fertiliser, as N {RER}| ammonium nitrate phosphate production | Alloc Def, U	-28	kg
Phosphate fertiliser, as P2O5 {RER}| ammonium nitrate phosphate production | Alloc Def, U	-7.7	kg
Potassium chloride, as K2O {RER}| potassium chloride production | Alloc Def, U	-20.6	kg
Nitrogen oxides	-646	g
Dinitrogen monoxide	-423	g
Ammonia	-2.2	kg
1_farming_on farm emissions		
Nitrogen oxides	612	g
Methane	3.7+16.2	kg
Dinitrogen monoxide	553	g
Ammonia	7.6	kg
1_farming_transport of feed		
Transport, freight, lorry 7.5-16 metric ton, EURO5 {GLO}| market for | Alloc Def, U	411	tkm
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	4094	tkm

2_SLAUGHTERING	per pig (104 kg)	
2_slaughtering _waste water		
BOD5, Biological Oxygen Demand	0.21	kg
Nitrogen	0.52	kg
2_slaughtering_black slaughterline		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.257* water_slaughter	kg
Carbon dioxide, liquid {RER}| market for | Alloc Def, U	0.56/2	kg
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.1*el_slaughter	kWh
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	0.23*ng_slaughter*natgas_dens*natgas_htv*10^3	MJ
2_slaughtering_boiler		
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	0.71*ng_slaughter*natgas_dens*natgas_htv*10^3	MJ
2_slaughtering_chilling		
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.4*el_slaughter	kWh
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	0*ng_slaughter*natgas_dens*natgas_htv*10^3	MJ
2_slaughtering_clean slaughterline		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.2436* water_slaughter	kg
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.1*el_slaughter	kWh
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	0*ng_slaughter*natgas_dens*natgas_htv*10^3	MJ
2_slaughtering_cleaning		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.1661* water_slaughter	kg
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.14*el_slaughter	kWh
2_slaughtering_cutting		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.0461* water_slaughter	kg
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.05*el_slaughter	kWh
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	0*ng_slaughter*natgas_dens*natgas_htv*10^3	MJ
2_slaughtering_deboning		
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.1*el_slaughter	kWh
2_slaughtering_energy recovery		
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	-0.58-0.83	kWh
2_slaughtering_evap cooling		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.035* water_slaughter	kg
Electricity, medium voltage {DK}| market for | Alloc Def, U	0*el_slaughter	kWh
2_slaughtering_organ processing		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.0965* water_slaughter	kg
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.06*el_slaughter	kWh
2_slaughtering_others		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.0804* water_slaughter	kg
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.03*el_slaughter	kWh
2_slaughtering_transport from farm		
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	240*104/1000	tkm
2_slaughtering_ventilation		
Electricity, medium voltage {DK}| market for | Alloc Def, U	0.02*el_slaughter	kWh
2_slaughtering_wash area		
Tap water {CH}| tap water production, underground water with disinfection | Alloc Def, U	0.0752* water_slaughter	kg
Heat, central or small-scale, natural gas {CH}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Def, U	0.01*ng_slaughter*natgas_dens*natgas_htv*10^3	MJ

Parameters used in slaughtering are given bellow:

el_slaughter	38000000/2780000	kWh/pig	electricity used in slaughterhouse (38 GWh/year 2780000 pigs per year)
ng_slaughter	3900000/2780000	Nm3/pig	Natural gas in slaughterhouse
water_slaughter	197	l/pig	Water in slaughterhouse
natgas_dens	0.8/1000	Kg/l	Natural gas density
natgas_htv	49	MJ/kg	Natural gas heating value

2c_SLAUGHTERING -AVOIDED Production	per pig (104 kg)	
2c_ avoided biogas		
Heat, district or industrial, natural gas {Europe without Switzerland}| heat and power co-generation, natural gas, 1MW electrical, lean burn | Alloc Def, U	-0.02*104*0.78*49	MJ
2c_ avoided feed		
Cattle for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.46*0.075*104	kg
Chicken for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.01*0.075*104	kg
Sheep for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.53*0.075*104	kg
2c_ avoided pharma		
Cattle for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.46*0.001*104	kg
Chicken for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.01*0.001*104	kg
Sheep for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.53*0.001*104	kg
2c_ avoided rendering		
Cattle for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.46*0.072*104	kg
Chicken for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.01*0.072*104	kg
Sheep for slaughtering, live weight {GLO}| market for | Alloc Def, U	-0.53*0.072*104	kg

Assumptions for the avoided production:

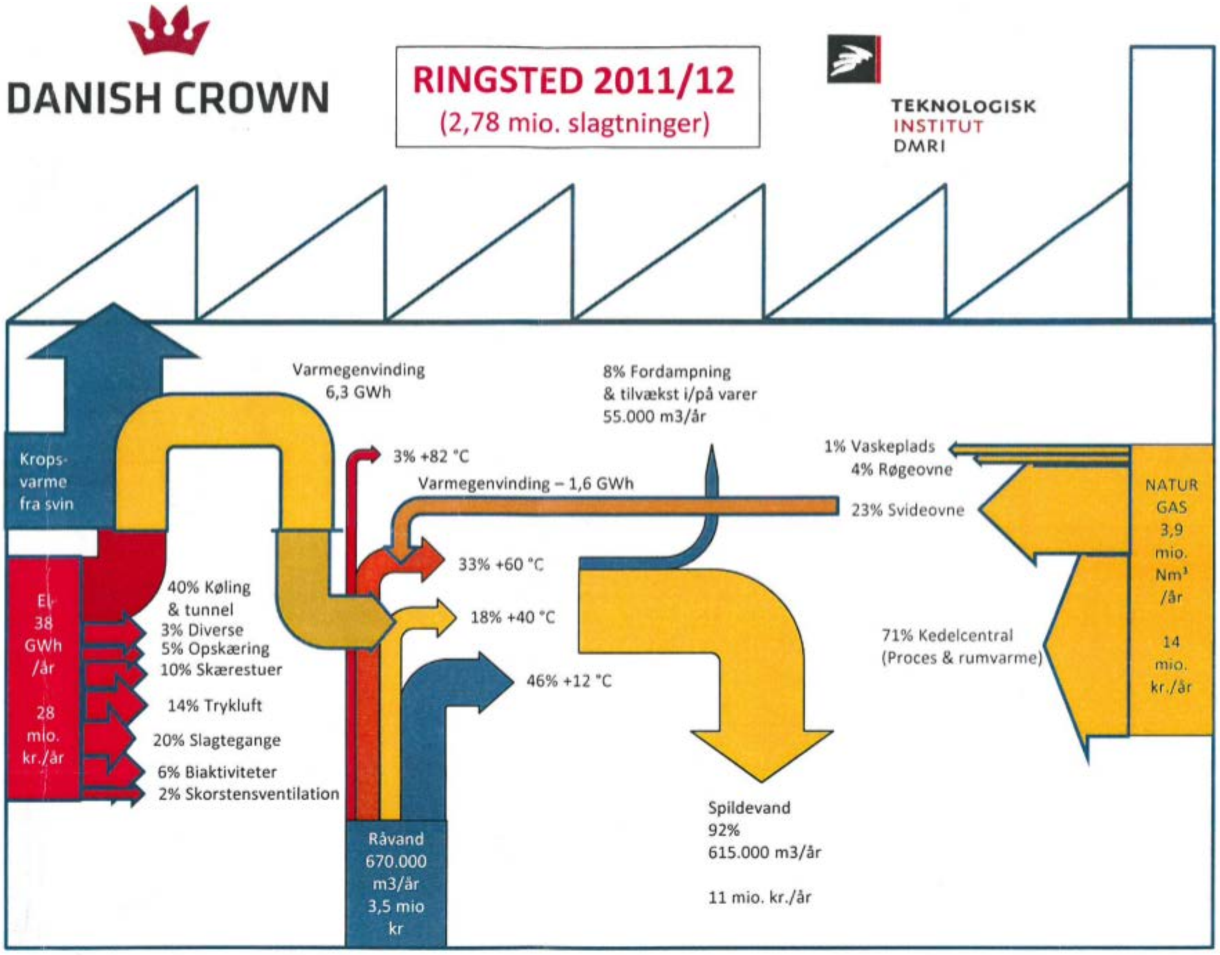
a) The fat used for biogas is 2% of live weight and it substitutes natural gas. Assumed heating values for fat: 38mj/kg. For natural gas: 49 mj/kg. 1 kg of fat corresponds to 0.78 kg natural gas (NG density 0.0008kg/l)

b) In the table above the first value shows the split between meats to account for 'average' (46% cattle, 0.1% chicken, 53% sheep). The second is the % wt that goes for secondary use per animal slaughtered (7.5% feed, 0.1% pharma, 7.2% rendering)

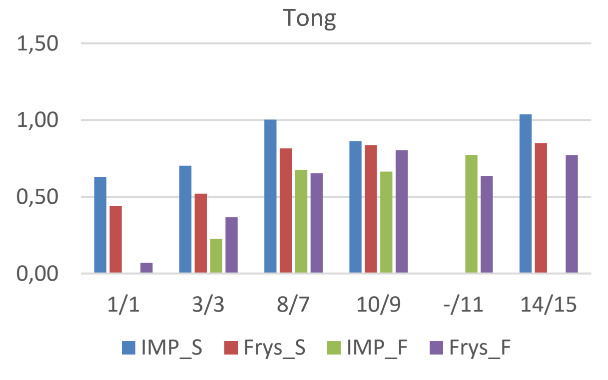
COOLING	per kg cut		
3_cooling general			
Carbon dioxide, liquid {RER}| market for | Alloc Def, U	0.56/2/104		
3_cooling_CO2			
Carbon dioxide, liquid {RER}| market for | Alloc Def, U			
tenderloin	0.0023	kg	
rib bones	0.0021	kg	
minced meat	0.0022	kg	
whole ham	0.0019	kg	
belly	0.0018	kg	
tongue	0.0022	kg	
heart	0.0024	kg	
front feet	0.0023	kg	
3_cooling_COP 2.6			corresponds to electricity consumption for impingement and spiral
Electricity, medium voltage {DK}| market for | Alloc Def, U			
tenderloin	8.24	kJ	
rib bones	7.39	kJ	
minced meat	8.01	kJ	
whole ham	6.87	kJ	
belly	6.37	kJ	
tongue	7.93	kJ	
heart	8.48	kJ	
front feet	7.87	kJ	
3_cooling_COP 3.7			corresponds to electricity consumption for, immersion, contact
Electricity, medium voltage {DK}| market for | Alloc Def, U			
tenderloin	5.79	kJ	
rib bones	5.19	kJ	
minced meat	5.63	kJ	
whole ham	4.83	kJ	
belly	4.48	kJ	
tongue	5.57	kJ	
heart	5.96	kJ	
front feet	5.53	kJ	
Packaging film, low density polyethylene {GLO}| market for | Alloc Def, U	17.7/1000/3	kg	
3_cooling_freezing			
Electricity, medium voltage {DK}| market for | Alloc Def, U			
tenderloin	20.07	kJ	
rib bones	15.95	kJ	
minced meat	17.43	kJ	
whole ham	16.22	kJ	
belly	12.84	kJ	
tongue	17.3	kJ	
heart	18.85	kJ	
front feet	16.82	kJ	

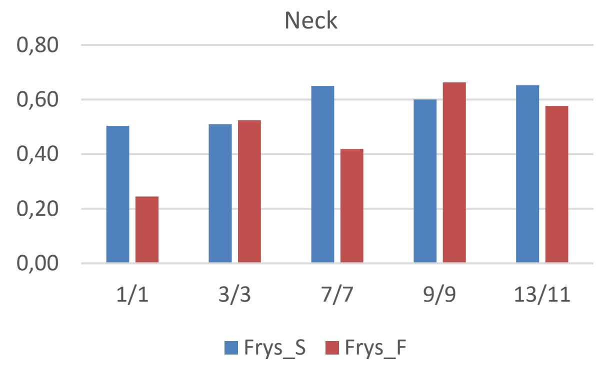
FROM COOLING TO CONSUMER	per kg cut		
4_packaging			
Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U	0.022*0.143	kg	
Polyethylene, low density, granulate {GLO}| market for | Alloc Def, U	0.022*0.143	kg	
Polyamide (Nylon) 6.6/EU-27	0.022*0.143	kg	
Ethylene vinyl acetate copolymer {GLO}| market for | Alloc Def, U	0.022*0.143	kg	
Polyethylene terephthalate, granulate, amorphous {GLO}| market for | Alloc Def, U	0.022*0.143	kg	
Polystyrene, general purpose {GLO}| market for | Alloc Def, U	0.022*0.143	kg	
Polyvinylchloride, emulsion polymerised {GLO}| market for | Alloc Def, U	0.022*0.143	kg	
Corrugated board box {RER}| production | Alloc Def, U	0.055	kg	
4_transport to markets			
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	267*0.001	tkm	DK (horsens to cph)
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	52*0.001	tkm	UK (DK -to port)
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	1221*0.001	tkm	UK sea
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	267*0.001	tkm	UK road
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U	(11052+17773)/2*0.001	tkm	CN sea
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	52*0.001	tkm	CN (DK -to port)
Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	267*0.001	tkm	CN road
4_cooling during transport			
Carbon dioxide, liquid {RER}| market for | Alloc Def, U	0.158124704	kg	fresh to japan
Carbon dioxide, liquid {RER}| market for | Alloc Def, U	0.013	kg	fresh todk/uk

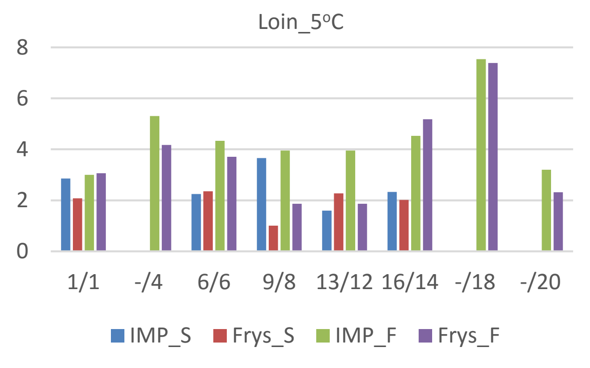
8.7 Ressource flows in the slaughterhouse

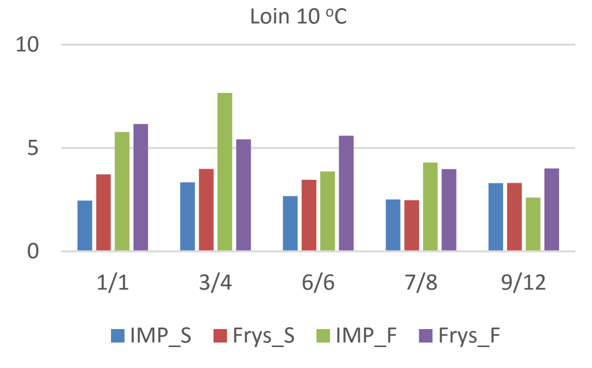


8.8 Drip losses for supper chilling (S) and freezing (F) through Impingement (IMP) and chilling room (Frys)


Tong


Neck


Loin_5ºC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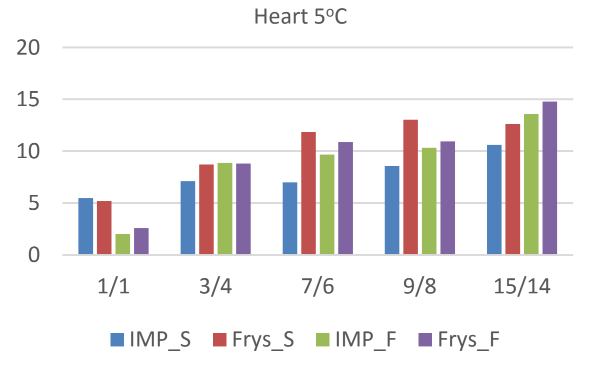
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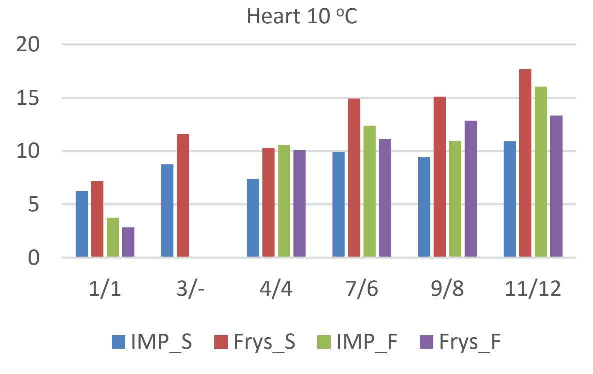
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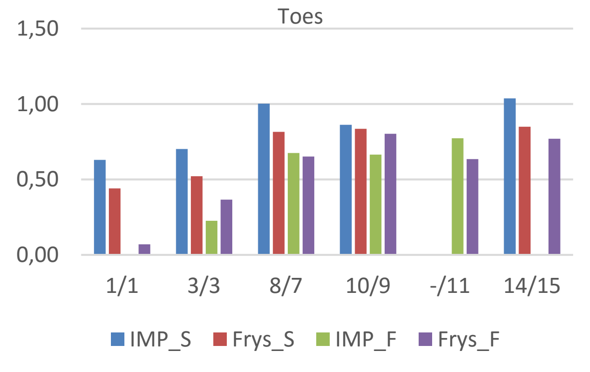
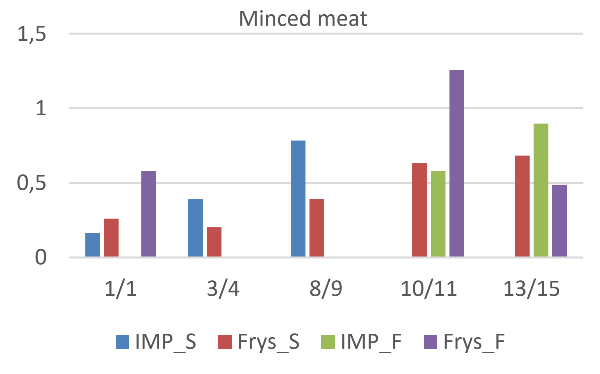

Toes


Minced meat