Towards sustainable food production: a scenario study of the European pork sector

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Abstract

European pork supply chains, like other agri-food supply chains, currently face numerous challenges such as globalization, emerging markets, changing consumer requirements, and new governmental regulations related to issues such as environmental pollution and food safety. These challenges require continuous innovation of supply chain network structures, reconsideration of business processes, relocation of logistics infrastructures and renewed allocation of chain activities to these infrastructures in order to achieve sustainable performances. This paper presents a scenario analysis of the spatial allocation of pork supply chain activities in Europe. Supply chain production and distribution activities are optimized in various scenarios based on economic and sustainability performance indicators. A mixed integer linear programming (MILP) model, which includes piglet production, fattening, slaughtering of pigs, processing of pork and pork consumption, is used to analyse the scenarios. The results reveal major opportunities for reductions in cost as well as in CO₂ equivalent emissions if a European sector perspective is taken and some chain activities are relocated to other countries. However, as minimizing costs will not always lead to an optimal reduction in CO₂ equivalent emissions, a differentiated strategy is needed for the European pork sector to move towards more sustainable production.

Keywords: pork supply chains, logistics, network redesign, sustainability, scenario analysis

1. Introduction

In a rapidly changing environment European agri-food supply chains need to address questions such as which plants to operate where, what product mix to produce at each plant, and which customer to supply from which distribution centre (Tsiakis and Papageorgiou, 2008). Supply chains and global corporations are confronted with the continuous challenge of evaluating and configuring their production and distribution systems and choosing logistics strategies that provide the desired customer service at the lowest possible cost. The context of geographical and political boundaries is changing rapidly due to the formation and/or further strengthening of trade alliances. While at the same time, global corporations themselves are constantly merging, acquiring, and divesting suppliers, product groups, and customer markets (Goetschalckx *et al.*, 2002). Therefore globalization causes a significant increase in cross-border flows of food products, which results in more complex relationships in agri-food supply chains (Aramyan, 2007; Van der Vorst *et al.*, 2009).

Moreover, there is a growing need to integrate environmentally sound choices into supply chain research and practice (Wognum *et al.*, 2011). In recent years, consumers and governments have been pressing companies to reduce the environmental impact of their products and processes (Quariguasi Frota Neto *et al.*, 2008). In response, agri-food supply chains have been pursuing more sustainable development by adopting different sustainability concepts such as environment-friendly logistics networks with lower CO₂ emissions.

European pork chains are no exception to this trend. This paper analyses whether it is possible to reduce the environmental burden at competitive cost prices of the European pork sector as a whole by spatial re-allocation of different pork supply chain activities over European countries. Different scenarios have been formulated in collaboration with experts and the impact on performance is assessed using a mathematical programming model.

The remainder of the paper is organized as follows. Section 2 discusses the key developments in European pork supply chains. Section 3 describes the research methodology applied and Section 4 the mathematical model that has

been developed. Section 5 presents the scenarios that were formulated. Next, the relevant input data to the model is discussed in Section 6. Finally, the modelling results are discussed in Section 7 and the main conclusions and discussion are presented in Section 8.

2. Issues in the European pork supply chains

European pork supply chains are highly self-sufficient and currently hold a competitive position in the global market. However, this position is threatened by challenging countries like Brazil, Canada, China and the USA (Lehmann, 2009). In order to keep a competitive position in the world market the European pork sector should identify its strengths and weaknesses and address the challenges that it faces. Besides the challenges related to environmental sustainability, European pork production faces three major challenges (Bonneau and Lebret, 2010):

- increasing societal disapproval of intensive production systems in response to environmental and animal welfare problems;
- increasing competition in the world market of commodity meat due to rising newcomers in the field;
- threat of loss of diversity and locally adapted production systems due to economic pressure.

Thus, to maintain its competitive advantage over new players in the field, the European pork sector must develop innovative, integrated and sustainable food production chains of high-quality pork and pork products that match consumer demands as well as support economic and environmental sustainability. Production of high-quality pork and pork products is a complex process, involving multiple interacting stages (Lehmann, 2009). The most important stages in the European pork chains are breeding, farrowing, finishing, slaughtering, processing and retailing (Figure 1)

A key development in the European pork sector is up-scaling and concentration in different stages of the supply chain. Table 1 presents the concentration in pork supply chains in Europe at different stages. In the retail stage concentration is observed especially in Northern European countries, where the five largest retailers hold up to 90% market share, while in Southern European countries retail is distributed among many grocery shops (Wognum *et al.*, 2009). Concentration also varies at the slaughtering stage: in the Netherlands the largest slaughterhouse company covers up to 60% of the pork market and in Germany the three biggest companies cover up to 50% of the market, whereas there are still about 368 slaughterhouse companies active in France. In the processing and farrowing/finishing

Figure 1. A European pork supply chain (adapted from Trienekens and Wognum, 2009).

stages there are still many small processing companies across Europe, particularly in the Eastern and Southern European countries. A strong trend towards concentration can be seen in the feed industry, where in Germany and the Netherlands the 10 largest companies have over 50% and 65% market share for feed respectively. With regards to breeding, the Netherlands, Germany and Denmark have the largest breeding companies, which deliver pigs all over Europe (De Winter and Tacken, 2010; Wognum *et al.*, 2009). As can be seen from the above-mentioned numbers and from Table 1, the concentration level differs per chain stage. Several studies have shown that growth in consumption of pork per person is expected to continue in the new EU member states, with consumers focusing mostly on price (De Winter and Tacken, 2010; Hoste *et al.*, 2004; Trienekens and Wognum, 2009). Research in the Netherlands has shown that prices in pork supply chains are distributed rather unevenly across the entire supply chain, whereby a pig farmer receives around 40 eurocent per kg product (6% of the final sales price) for his own labour and capital, and a retailer receives about 24% of the sales price (Hoste *et al.*, 2004).

Several studies have also shown that greenhouse gas (GHG) emissions, expressed in g CO₂ equivalents, are rather high in pork supply chains (Carlsson-Kanyama, 1998; De Vries and De Boer, 2010; Mogensen *et al.*, 2009). This is partly caused by the relatively poor conversion of feed dry matter into meat products (e.g. pork, chicken and beef) (Mogensen *et al.*, 2009). De Vries and de Boer (2010) compared the carbon footprints of different livestock products in a recent review. This review revealed that beef has the highest carbon

Table 1. Concentration per stage in European pork supply chains (EC, 2009; Wognum *et al.*, 2009; De Winter and Tacken, 2010).

Feed stage	No. of companies
The Netherlands	10 firms >65% market share
Germany	10 firms >50% market share
Spain	15 large firms
France	252 small firms
Farrowing/finishing stage	No. of companies (in 1000)
Southern Europe	Many small farms
Hungary	316 from which 80 farms >50% total production
Spain	96 (very small)
Germany	80 (many small)
France	19.5
The Netherlands	8
Greece	0.74
Slaughterhouse stage	Ranking in European market
Denmark	1
The Netherlands/Germany	2
Germany	3
France	4
UK/Sweden	5
Processing stage	No. of companies
Southern Europe	Many small
The Netherlands	54 large
Spain	2 large >40% market share
Retail stage	Distribution channel %
Meat bought in supermarkets/hypermarkets ¹	
The Netherlands	91
Germany	79
France	77
Meat bought at butchers or night-shops	
Portugal	66
Malta	60
Bulgaria	53
Romania	49
Greece	46

¹ Meat refers not only to pork, but to all kinds of meat bought by consumers in Europe.

footprint, followed by pork and chicken, and this holds for carbon footprints expressed per kg of product, per kg of protein, or per typical daily intake in Europe. However, the paper also noted that while beef production does not entirely rely on feed that could be utilized by humans, the feed used for pork and poultry often competes with foods for human consumption. Thus it is inevitable that European pork supply chains will have to consider possibilities to substantially reduce greenhouse gas emissions, while at the same time meeting consumer demand and remaining competitive and economically sustainable.

Aside from contributing to concentration and environmental issues, globalization also introduces economic changes in labour, land and energy use, which in turn affect the capacity and attractiveness of foreign production. As a result of site-specific production benefits (e.g. food and raw material availability, labour, knowledge) pork is not necessarily produced at the location where it is consumed. This entails shifts in production processes. While Western European countries will most likely focus more on knowledge-intensive activities, it may be more profitable to shift labour-intensive activities to countries with low wages and more environmental space (e.g. Poland, Russia). Changing consumer requirements, new legal requirements related to food safety and environmental sustainability, and foreign competitors emerging on the market require European pork supply chains to innovate their network structure, consider spatial shifts in production, renew logistics initiatives and re-allocate chain activities. Thus the current study introduces an approach (focused on food sector level rather than on individual supply chains) that illustrates whether, by shifting pork supply chain activities throughout European countries, it is possible to reduce the environmental burden with regards to CO₂ equivalent emissions while keeping the costs involved as low as possible.

3. Research methodology

To study a system of interest, we often have to make a set of assumptions about how it works. These assumptions are used to create a model that in turn is used to try to gain some insight into the behaviour of the corresponding system. Problems are often modelled either by means of mathematical or simulation methodologies; their application depends on the task at hand (Van der Zee and Van der Vorst, 2005). If the relationships that compose the model are simple enough, it may be possible to use analytical methods (such as algebra, probability theory or linear programming) to obtain exact information on questions of interest. If the problem is to be studied at the operational level, it usually becomes too complex to allow for analytical modelling, and these models are preferably

studied by means of simulation (Law and Kelton, 2000; Van der Vorst *et al.*, 2009). Hence, looking at supply chain problems, mathematical programming models are usually used to optimize tactical/strategic decisions to determine configurations such as supply chain network design or distribution structures. Simulation models are mainly used to study the detailed dynamics of a fixed configuration under operational uncertainty and can be used to evaluate expected performance measures with a higher level of accuracy (Papageorgiou, 2009).

Since the subject of this study is the configuration of the European pork supply chain (i.e. decision making on strategic level) the applied method is mathematical programming. A large number of tools and techniques have been used for mathematical programming, such as dynamic, multi-period, deterministic or stochastic models. Linear programming is the most common technique used to formulate and solve optimization problems followed by dynamic programming (Srivastava, 2007). Other non-linear programming models have also been utilized. An often-cited work in this area is Cohen and Lee (1989), who presented a deterministic, mixed integer, non-linear mathematical programming model, based on economic order quantity (EOQ) techniques, to develop a 'global resource deployment' policy. More specifically, the objective function used in their model maximizes the total after-tax profit for the manufacturing facilities and distribution centres. Other authors have extended this work. For example, Jackson and Grossman (2003) describe a multi-period non-linear programming model for the production planning and distribution of multi-site continuous multi-product plants, where each production plant is represented by nonlinear processes. An MILP model is proposed by Timpe and Kallrath (2000) for the optimal planning of multi-site production networks. The model was applied to a production network of four plants located in three different regions.

The need to improve the sustainability of the chain from an economic and environmental point of view has stimulated development of integrated frameworks that combine economic and environmental aspects. This requires a quantification of the environmental impact of a supply chain (e.g. by means of Life Cycle Assessment (LCA) based indicators) and the use of these measures in optimization models, potentially leading to multi-criteria frameworks (Papageorgiou, 2009). An example of such a framework is found in Zhou *et al.* (2000), where the authors describe a goal programming approach to account for sustainability aspects of supply chains with continuous processes. Another example is the work of Hugo and Pistikopoulos (2005), in which the authors combined the LCA criteria with design and long-run planning of multi-enterprise supply chain

networks in an optimization model and applied it to a bulk chemicals supply chain. Günther and Kannegiesser (2010) illustrated how sustainability performance can be integrated and optimized in a long-term strategic network design problem in the packaged food industry, by applying a mixed-integer linear optimization model. This study specifically investigated the impact of different CO₂ pricing scenarios for the transportation sector on overall network design.

Although mixed integer programming models are among the most widely used techniques to address the improvement and optimization of supply chains, most models address the problem in a regional, local, or single-country environment, where international factors do not have a significant impact on the design of the supply chain (Goetschalckx *et al.*, 2002). Our study follows Timpe and Kallrath (2000) and uses a straightforward mixed integer linear programming model (MILP) with a summed timespan of one year that integrates two aspects: environmental sustainability and economics. It also addresses the problem in a multi-country environment (with its specifics), since it focuses on the European pork sector.

Research process

A supply chain analysis was conducted as part of the European KP6 Q-PorkChains project (Wognum *et al.*, 2009). This analysis provided insight into the supply chain activities and processes forming the basis for the MILP model. Preliminary versions of the model and results were discussed with experts, resulting in relevant adjustments according to current practices. The developed model was then discussed in six expert meetings in which a baseline scenario was agreed upon and relevant scenarios for sustainable European pork supply chains were defined. The discussion sessions were held during the public Q-PorkChains conferences (Bonn 2009, Dublin 2010), project meetings (April 2009, May 2010) and bilateral discussions with the industry (November and December 2010).

Model description and assumptions

The developed MILP model is able to analyse supply chains of agricultural products in the context of economic costs as well as environmental impact. In the first case the model minimizes total cost of all supply chain activities using cost parameters (such as Euros per km for transport cost). In the second case, the model minimizes the environmental impact using kg CO₂ equivalents (such as kg CO₂ per km transport). Furthermore, we were also able to convert the kg CO₂ equivalents into costs, which makes it possible to integrally minimize the process costs plus the environmental impact.

The model was applied to the pork sector comprising supply chain activities in seven European countries: the Netherlands (NL), France (FR), Germany (GE), Denmark (DK), the United Kingdom (UK), Poland (PL) and Russia (RU). The production streams within these countries and between them and countries in the rest of the world were taken as constant and therefore disregarded to exclude fixed production in the seven countries. The pork supply chains considered in this study consist of piglets (and sows), slaughter pigs, slaughtering, pork processing and pork consumption. Furthermore, the following model assumptions were made:

- A1 The production flows among the seven aforementioned European countries are considered in the scenarios. Although the production flows between these countries and the rest of the world are taken as constant, they do not affect the trade in these countries.
- A2 An animal or meat product goes through the production processes of the country where it is located. So if a piglet is imported into Germany from France, the piglet will be fattened according to the German feed regime and cost structure.
- A3 The consumer is located at the geographical centre of a country.
- A4 The production processes are all located in the area where the country's production actually takes place.
- A5 Piglets in different countries have different end weights. To compensate for this, costs are adjusted to a 'standard' piglet of 30 kg.
- A6 Slaughter pigs in different countries have different slaughter weights. Costs are adjusted to a 'standard' slaughter pig of 90 kg slaughter weight.
- A7 New production systems in Poland are expected to be as modern as in Western Europe. The cost structure of new production and slaughtering methods is adjusted to new production systems.

Scenario description

To show cost reduction as well as sustainability improvement opportunities, three scenarios involving the relocation of pork chain activities were defined. The baseline for these scenarios is the situation of 2009 (current pork chains). The first scenario is a cost optimization of the baseline situation, the second scenario is a CO₂ eq. optimization of the baseline situation and the third scenario is a combination of both data. Based on sessions with experts, the following issues were taken into account in the developed scenarios:

- Level of self-support: A country that is a net exporter of pork incurs higher costs than a country that produces below its level of consumption. A price component is incorporated in the model with the price increase as a

flexible parameter (%) to be used as sensitivity analysis. This is to create a barrier when a country becomes a net exporter; the assumption being that when this happens, extra costs are made. This might include transport costs, expenses related to establishing a distribution channel, or production costs (Bernard and Bradford Jensen, 1999).

- Trust: Although prices for production in Eastern European countries might be lower than in the western part of Europe, financial trust is lacking because of the long term of payments and corruption (Johnson *et al.*, 2000).
- Differentiation: One of the important topics of discussion with experts was whether to differentiate between types of production systems within countries. Because widely different production systems exist in Poland, a distinction was made between classic production (small-scale family farm with low performance) and modern integrated production in that country.

The first two issues were used to perform sensitivity analysis to test the robustness of the model, while the last issue was incorporated into the model.

Baseline situation of pork supply chain

The following supply chain costs were used to determine a 2009 baseline situation: production costs of piglets (including feed for sows) and slaughter pigs, and slaughtering, processing and transportation costs. The 2009 levels for production and slaughtering and the import and export of piglets and pigs into and out of each country were also used. Consumption of pork in each country was used as the end of the supply chain. Pork was not further separated into different segments or other products to overcome difficulties with different products coming from the same part of the pig.

Scenario 1 Cost-optimized pork chain

In Scenario 1 the baseline situation described above was optimized with respect to cost. Production level per country is variable (so production and processing activities can be relocated), while the consumption level is fixed.

Scenario 2 CO₂ eq. optimized pork chain

The same model structure was used as above in Scenario 1, but the costs of producing piglets, pigs and pork were replaced by kg CO₂ eq. production. In addition, kg CO₂ eq. per km was used instead of transport costs.

Scenario 3 Combined cost and CO₂ eq. optimized pork chain

To combine costs and CO₂ eq. an approach was chosen to convert CO₂ equivalents into financial value. An average of the EU emission allowances over time is a way to express the equivalents in Euros (Ellerman *et al.*, 2010). The costs of CO₂ emissions were internalized in the costs of production. 20 Euro per tonne CO₂ eq. was used. In this way the environmental data was quantified and added on top of the costs of Scenario 1. The same model structure as in Scenario 1 was used.

Model robustness

As mentioned above the model results were tested for robustness. Some variations in costs were made to find out whether this changed the model results. The figures used for this purpose were derived based on expert meetings and literature. Transparency International (2009) publishes a corruption perception index of countries on a scale from 0 (highly corrupt) to 10 (very clean), and Johnson (2000) gives clues as to how this index can be translated into a cost factor. Based on these publications, the following additions were made to the actual costs. An additional 10% was added to production costs in countries ranked in the lowest 33.3% of the 0 to 10 scale. For those ranked in the middle 33.3%, 5% was added and no extra amount was added to production costs in countries with the lowest corruption levels (Table 2).

4. Input data

This section describes the economic and environmental input data used to analyse different scenarios.

Table 2. International corruption perception index (Transparency International, 2009).

Country	Corruption perception index	% cost adjustment
Denmark	9.3	0
The Netherlands	8.9	0
Germany	8	0
United Kingdom	7.7	0
France	6.9	0
Poland	5	5
Russia	2.2	10

Economic data

The farm production costs were derived from the InterPIG¹ network and from the study of Hoste (2011). Costs are expressed per piglet and per kg of slaughter weight respectively and then, according to the InterPIG method, recalculated to a standard weight of 30 kg for piglets and 90 kg hot slaughter weight for the slaughter pigs. Next, costs were estimated for slaughtering and processing, based on Hoste and Bondt (2006) with a 15% increase to compensate for devaluation between the literature results and 2009. These costs are expressed per tonne of carcass weight. Like farm production costs, slaughter and processing costs for the non-western countries were estimated based on known figures of the other countries. Standardized cost prices as modelled in the MILP model are expressed in Euros per animal and Euros per tonne pork. More data on different components of the cost structure can be found in Table 3. As shown in Table 3, production costs vary between countries. For instance, the cost of producing a 30 kg piglet is about 25% higher in Russia and Poland (for a classic production system) than in Denmark. A similar pattern can be observed at the fattening, slaughtering and processing stages.

Environmental data

The carbon footprint (CFP) or global warming impact potential (GWP) measures the impact on the environment in terms of the amount of greenhouse gases produced throughout the product life cycle. The footprint is commonly expressed in CO₂ equivalents, i.e. accounting for the 100-year GWP of CH₄ and N₂O relative to CO₂ of 25:1 and 298:1 (IPCC, 2007), respectively. The developed model was set up for logistics optimization with regard to the global warming impact (carbon footprint) of producing piglets and slaughter pigs in different countries, taking into consideration differences in production efficiency as well as manure management practices. In general differences between countries exist with respect to animal performance levels, feed composition in terms of energy, protein and phosphate content, housing systems and manure management systems (storage and application). These differences were also taken into account. An intensive pig production system typically includes piglet and slaughter pig production units. The piglet production unit produces

¹ InterPIG is an international group of pig production economists of 14 countries, covering mainly Western Europe, but also Canada and Brazil (<http://www.lei.dlo.nl/wever/docs/InterPIGEngels.pdf>). Hoste (2011) described the InterPIG network in his study about the production costs of pigs (see references for more details).

Table 3. Cost structure of piglet and slaughter pig production, slaughtering and processing in different countries.

Costs	DK	NL	DE	FR	UK	PL (classic)	PL (modern)	RU
Production cost of piglets (€/piglet)	49.98	45.71	58.88	50.50	63.82	66.00	51.00	66.00
Piglet weight (kg)	31.40	25.10	29.90	31.57	36.6	35.00	30.00	35.00
Piglet production cost at harmonized 30 kg (€/piglet)	48.57	50.59	58.97	54.12	57.22	61.00	51.00	61.00
Production cost of finishing pig (€/kg live weight increase)	0.86	0.91	0.92	0.80	1.23	1.02	0.75	1.02
Cost of finishing pig at harmonized 90 kg slaughter weight (€/pig)	71.79	75.64	76.29	66.57	102.58	86.82	64.05	86.82
Total costs finishing pig (€/pig)	142.03	153.16	168.71	143.15	191.17	166.16	133.51	166.16
Mortality rate of finishers	4.10%	2.40%	3.10%	3.60%	3.20%	4.50%	3.00%	4.50%
Slaughtering costs (€/slaughter pig)	17.58	15.65	15.15	16.16	19.55	17.25	14.09	14.09
Processing costs (€/kg carcass weight)	0.60	0.46	0.37	0.48	0.52	0.41	0.41	0.41
Live weight of slaughter pigs (kg)	106.70	118.20	119.80	115.80	103.30	98.50	110.00	98.50
Carcass weight of slaughter pigs (kg)	81.40	92.10	94.60	90.90	79.80	76.83	86.90	76.83
Slaughter and processing costs, harmonized weights (€/tonne carcass weight)	793.37	633.91	536.28	662.53	734.72	605.67	570.52	570.52

piglets as the main product together with sows for slaughter; its inputs are feed and replacement gilts. The slaughter pig production unit produces finished pigs for slaughter, and its inputs are feed and piglets.

The main sub-system of piglet production and slaughter pig production is pig farming, consisting primarily of animal housing and manure management/manure utilization. Various sub-processes include the production of feed, transportation of feed and the production of energy (heat, electricity, and fuels) consumed at the farm. The key assumptions used in the analysis in relation to feed use and manure management/manure utilization are described below.

Feed use

Pig feed is a complex blend of ingredients originating from different sources. Using a consequential approach, it can be generalized that pork production is global and draws on global feed resources. Thus production of an extra pig will ultimately draw on a protein source (e.g. oilseed meal) and cereals (Bouwman *et al.*, 2006). The theoretical required amounts of marginal energy feed (barley, according to Schmidt and Weidema, 2008) and protein feed (soybean meal as argued by Dalgaard *et al.*, 2008) were calculated based on the amount of protein and energy supplied by the two feed ingredients to satisfy the protein and energy requirements of the pigs. With respect to the transport of

feed from the primary production site to the feeding site, it was assumed that soy bean meal is transported 12,000 km by ship and 900 km by truck, and local grain is transported 100 km by truck.

Manure management and use

The manure excreted by the animals in the form of slurry (i.e. a mixture of liquid and solid particles) is first stored in a pit beneath the slats (i.e. stables) for a short interval and then transferred to the external storage tank where it is ready for the next step, e.g. field application. The emissions of especially CH₄ and N₂O from manure storage depend on a number of conditions, such as housing system, temperature, in-house storage duration and outside storage with or without cover (IPCC, 2006).

After storage the manure was assumed to be used as fertilizer elsewhere outside the farm. This manure was assumed to substitute mineral fertilizers to some extent depending on the actual availability for crops and environmental regulations. The substitution rate for the three major nutritional elements in manure, nitrogen, phosphorous and potassium, was supposed to reach 75, 100 and 100%, respectively (Nguyen *et al.*, 2010), which reflects regulations for the use of manure in Denmark. The level of manure utilization may differ among countries, but for the sake of simplicity, we assumed this Danish rate for all the countries in the study.

GWP-LCA calculation

The carbon footprint per kg piglet and slaughter pig was calculated using the standard LCA methodology, which combines on-farm GHG emissions with emissions from inputs of feed, transport, heat, electricity and farm traction. To estimate on-farm emissions we used emission factors available from literature, mainly IPCC (2006). In current LCA studies on livestock products, the 2006 IPCC guidelines are commonly used to obtain default factors to estimate in particular methane and nitrous oxide emissions from manure management and application. For more information on how we calculated on-farm emissions the reader is referred to Nguyen *et al.* (2010). GHG emissions or the carbon footprint of feed (barley and soybean meal), transport, heat, electricity and farm traction were derived from Nielsen *et al.* (2003) and Dalgaard *et al.* (2008). Next we will present the calculated input data for feed and pig production.

LCA data for feed

The carbon footprint values of feed – barley and soybean meal – as well as other commodities associated with the system are presented in Table 4. In this work, the life cycle inventory of barley established by Nielsen *et al.* (2003) was updated, taking into account: (1) current crop yield and fertilizer input; (2) implementation of new technology to reduce the carbon footprint of nitrogen fertilizers; and (3) the updated 2006 IPCC guidelines for estimating on-farm emissions. The LCA of soybean meal was conducted and published by Dalgaard *et al.* (2008). Soybean meal and soy oil are co-products of soybean production. To distribute the environmental loads from soybean farming and processing between the two co-products we used system expansion

to avoid allocation. The soybean production system was thus expanded to include the cultivation of oil palms. This reflects the assumption that the soy oil produced together with the soybean meal will substitute other vegetable oils e.g. palm oil. As a result, there will typically be a lower need for oil palm production. In this analysis, we update the LCA of soybean meal by adopting the inventory of ‘soybean cultivation’ and ‘oil palm cultivation’ available in the Ecoinvent database (<http://www.ecoinvent.org/home/>) and a published dissertation (Schmidt, 2007), respectively.

LCA data for pig production

The results of GHG emissions impact for piglets and slaughter pigs, expressed per animal and per kg, are given in Table 5. The results reflect a relationship between feed use rate, i.e. the amount of feed input (either in mass or protein nitrogen), per unit of meat output and GHG emissions impact. The lower the feed use rate, the lower the impact. Besides resulting in a low GWP related to feed production and transport, a low rate of feed input in terms of dry matter and protein per unit of meat output also results in low emissions related to manure handling. Out of the farming systems, Poland (classic farm type), Russia and the UK have the largest impact owing not only to low production efficiency but also to a high level of GHG emissions related to manure management.

The CO₂ eq. calculations (Table 5) were recalculated to equal weights for the piglets (30 kg) and slaughter pigs (90 kg slaughter weight). Based on feed consumption, it was assumed that 35% of the CO₂ eq. emissions from the piglet production is assigned to the piglets and the rest to the sows. Therefore the difference in piglet weight between 30 kg and the country-specific weight was multiplied by 35% of the ‘kg CO₂e/kg of piglet’ and added to the country-specific

Table 4. Carbon footprint of major commodities associated with the pig production system.

Item	Unit	g CO ₂ e	Data sources (adapted or taken directly from)
Feed	Barley	kg	507
	Soybean meal		347
Energy	Heat (oil)	MJ	94
	Electricity (gas)	kWh	655
	Traction	MJ	109
Fertilizer	N	kg	5,440
	P		2,690
	K		804
Transport	Ship	tkm	9
	Truck 28t		227
	Tractor and trailer		306

Table 5. GHG emissions impact (carbon footprint) of piglet and slaughter pig production in selected countries.

	DK	NL	DE	FR	UK	PL classic	PL modern	RU
Piglets								
Weight per piglet weaned, kg	31.4	25.1	29.9	31.6	36.6	35	30	35
kg CO ₂ e/piglet (excluding sow meat)	86	69	86	88	109	136	95	136
kg CO ₂ e/kg of piglet	2.74	2.73	2.88	2.79	2.99	3.89	3.15	3.89
kg CO ₂ e/kg of piglet, harmonized 30 kg	85	74	86	86	102	129	95	129
Slaughter pigs (per pig produced)								
Weight at slaughter, kg	106.7	118.2	119.8	115.8	103.3	98.5	110	98.5
Piglet input needed, number	1.04	1.03	1.03	1.04	1.07	1.03	1.03	1.03
kg CO ₂ e/slaughter pig (excl.piglet)	192	237	253	219	198	176	204	176
kg CO ₂ e/kg of slaughter pig	2.55	2.55	2.82	2.60	2.97	2.78	2.55	2.78
kg CO ₂ e/sl.pig, harmonized 90 kg slaughter weight	212	212	235	216	247	237	218	237

'kg CO₂e/piglet (excluding sow meat)' to assess the CO₂e per 30 kg piglet. With the slaughter pigs, the equalized live end weight was deducted by 30 kg and multiplied with the country-specific 'kg CO₂e/kg of slaughter pig' (Table 5). Data from Table 5 were used as input to the model to optimize the sustainability of the pork supply chains.

5. Modelling results

We modelled the different scenarios using the input data described in the previous section and let the model search for the optimal allocation plan. The modelling results are presented in Figure 2. Compared to the baseline scenario the alternative scenarios show major shifts in

production locations, indicating significant opportunities for improvement.

The outcome of Scenario 1 (cost optimization) reveals that the production of piglets shifts completely to Denmark. Also in this scenario the production of slaughter pigs shifts to Poland, whereas slaughtering and the processing (together represented in the figure as 'pigmeat') shifts to Poland and Germany. This large degree of shift compared to the baseline scenario is possible because transportation represents only a small portion of total costs in the supply chain. The optimized solution is more or less equal to allocating production to the country with the lowest production cost per derived unit. Denmark has the lowest production costs for piglets and slaughter pigs and, therefore, the majority

Figure 2. Production of piglets, slaughter pigs and pork in different countries for scenarios 1, 2 and 3.

of production takes place in this country. There are hardly any trade-off effects.

Scenario 2 shows quite different results, with a shift of the entire piglet production to the Netherlands, and slaughter pig production to the Netherlands and Poland. This is caused by the relatively low level of CO₂ emitted for the production of piglets and pigs in the Netherlands. Slaughtering and processing do not contribute significantly to CO₂ emissions, so this category is not visible for this scenario in Figure 2.

The optimization of costs combined with the optimization of CO₂ eq. emissions in Scenario 3 yields comparable results as the optimization of costs only (Scenario1), however all slaughtering and processing shifts to Poland. While Figure 2 presents the results of each scenario per country, Figure 3 presents the combined results for the seven countries for each scenario.

Figure 3 shows that costs can be reduced by about 17% in Scenario 1 compared to the baseline scenario. If production is optimized based on both costs and costs for CO₂ eq. compensation (Scenario 3), the total cost reduction is approximately 14%. In Scenario 1 the costs of piglet production are reduced from 34 to 24% of the total, and the cost share of the fattening stage is increased by about 6%, whereas the costs of slaughtering and processing are reduced from 40 to 24%. However, transport costs increase from 1 to 4%.

Figure 4 shows a more than 20% decrease in CO₂ eq. emissions in the optimized Scenario 2, made up on the one hand by a decrease in emissions in piglet and pig production, and on the other hand by a fourfold increase in CO₂ emission through transport.

Figure 3. Aggregated production costs for the baseline scenario, for scenario 1 (cost optimization) and for scenario 3 (combined optimization) (Baseline = 100%).

Figure 4. Aggregated CO₂ equivalents for baseline scenario and for scenario 2 (CO₂ eq. optimization).

Sensitivity analysis

In order to test the robustness of the results a sensitivity analysis was performed on two aspects considered to be important during the expert discussion sessions: corruption level and self-sufficiency of the country (Figure 5). Since these two aspects do not affect the CO₂ eq. emissions, a sensitivity analysis was performed for only Scenarios 1 and 3. As presented in Figure 5, correcting for corruption and self-sufficiency did not affect the results of Scenario 1, and had only a slight impact on the results of Scenario 3, suggesting a shift in production between countries.

6. Conclusions and discussion

This study shows that relocating production activities on sector level in Europe, rather than on chain level, provides opportunities for reduction of CO₂ equivalent emissions and total costs. Moreover, minimizing costs leads to a rather different spatial allocation than optimizing CO₂ eq. emissions, which suggests that cost efficiency and maximum sustainability do not go hand in hand in this case. Compared to production, transportation is of minor concern for both cost and CO₂ eq. emissions. In other words, differences regarding cost (and/or CO₂ eq.) related to production are the main determinants of the optimal spatial allocation.

The results show each country has regional advantages at some stages of the supply chain but only moderate results in other stages. For example piglet production in Denmark is very cost effective, but slaughtering and processing are expensive. Results show that costs or CO₂ eq. emissions can be reduced if production at each stage takes place in the

country with the lowest costs or emissions (respectively) for that stage. However, optimal costs will not always lead to optimal CO₂ eq. emissions, so to optimize both additional measures would be needed. To reduce costs, CO₂ eq. emissions or both in Europe, new strategies will have to be formulated. Therefore, we conclude that a differentiated strategy is needed for a transition towards a more sustainable pork sector in Europe.

As always in modelling studies, care must be taken when interpreting the results. As we analysed the system on a very high (sector-wide) level, much of the data are approximations and will differ from detailed (real-life) supply chain level data. For example, the dynamics of investment possibilities were not taken into account. Small changes in production cost or production CO₂ eq. emission may change the optimal spatial allocation. In reality, it takes much longer for a production system to adapt to changes in production costs because of long-term investments that have already been made. The model does not take this (nor disinvestment costs) into account. Several other aspects which have not been taken into account in the present study probably also impact strategic location decisions: the proximity between trade partners (impacting product freshness, time to deliver and animal welfare), reputation, transaction costs, risk (currency exchange fluctuations, payment security), etc.

Considering the broad view taken in this study and assumptions made, there are many opportunities for further research. To conclude, we will mention the following three:

- Research should investigate opportunities and means for national and EU policy makers to stimulate EU regions to specialize in particular pork production activities to enhance sector sustainability within the EU.

Figure 5. Sensitivity analysis for Scenario 1 (A) and Scenario 3 (B).

- Relocation of production requires a willingness to move among entrepreneurs, which is not always the case for farmers, as Silvis *et al.* (2002) have shown.
- How will consumer preferences ('local to local', 'buy British', etc.) impact the optimal allocation plan? These aspects will put major restrictions on reallocation options for production activities.

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