The economic and environmental performance of distribution networks: A case study from the petrochemical industry

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Abstract: Designing a company's distribution network is a challenging task that requires the consideration of different aspects. In this respect, especially trade-offs between, for example, operational costs and customer service are the focus of the companies' attention. However, growing concerns of governments and customers about environmental protection have raised awareness towards the environmental impact of operations. Activities associated with the distribution of products, i.e. transportation and warehousing, are not yet subject to strict environmental regulations, but this situation is expected to change soon. Companies must, therefore, start to concentrate not only on economic but also on environmental aspects in the design of their supply chain. Based on a case study from the petrochemical industry, this paper presents a way to combine both, economic as well as environmental criteria, when evaluating (strategic) distribution network design decisions. The results show a trade-off between total (distribution) costs and transport carbon emissions.

1 Introduction

The distribution stage comprises all processes that are necessary to move and store products on their way from the production stage to the customer, thus consisting of transportation and warehousing activities (Chopra and Meindl 2010). For a company, the structure of its distribution network is of significant importance because several trade-offs must be considered, for instance between operational costs and customer service. In this respect, decision-support systems are used that usually aim at optimizing economic objectives. However, the growing concerns of both governments and customers about environmental protection and about the reduction of greenhouse gases force companies to think of integrating environmental criteria into decision making.

There are already different environmental regulations in force in the European Union, like the EU Emission Trading Scheme (ETS) or the Waste Electrical and Electronic Equipment (WEEE) directive. Further regulations are expected to come, yet activities associated with the distribution of products are not yet subject to strict environmental regulations with respect to greenhouse gas emissions. But since especially transportation is responsible for a considerable amount of greenhouse gas emissions, this situation is expected to change in the near future. Hence, companies are well advised not only to concentrate on criteria for economic, but also environmental performance, when making supply chain decisions.

Based on a case study with one of the leading petrochemical companies in Southeastern Europe, this paper presents a way to combine economic as well as environmental aspects when evaluating (strategic) distribution network design decisions. The company in scope aims at restructuring its distribution network with a special focus on reducing the number of local storage locations. While the company's main objective is to reduce its distribution costs, it also focuses on assessing and improving its environmental performance in terms of carbon emissions from transportation. For that purpose, a facility location model is developed that shows the impact of different network design scenarios on costs and transport carbon emissions. In addition, the impact of a possible future regulation, namely the imposition of carbon costs, on the optimal network design is analyzed.

This paper is structured as follows. In Section 2 we take a close look at the impact of transportation on the environment. Section 3 provides an overview of facility location models and possible ways of extending them in order to integrate environmental aspects. The conducted case study as well as the modeling approach and the results are described in detail in Section 4. Section 5 concludes this paper by pointing out limitations of the model and further research opportunities.

2 Emissions from transport activities

Economic growth and the development of transportation are closely related. Although transport has long been considered as a simple necessity, it soon started to gain importance and to be an integral way of achieving competitiveness (Golicic et al. 2010). In the European Union, freight transport activities in terms of tonne-km increased steadily from 1995 to 2005, on average 2.8% each year. By comparison, the current transport activities in the EU27 would equate to moving one ton of goods over 23 km per day per inhabitant. The drastic rise in transport activities can largely be attributed to increases in road transportation (on average 3.5% per year), which is still the predominant transport mode in Europe. Currently, 47% of freight transport activities are carried out via this mode. Rail transportation increased only slowly, on average 1.1% each year in the same period of time, accounting for approximately 10% in terms of tonne-km in 2006 (Eurostat 2009).

The reasons for increased transport activities are, for example, the ongoing integration of the market and the liberalization of the transport market itself in combination with relatively low costs of freight transport. Furthermore, current business strategies and operations favor increased transport activity in many cases. As mentioned by Aronsson and Huge-Brodin (2006) as well as Golicic et al. (2010) practices like global sourcing or just-in-time deliveries accelerate the recent growth in the transport sector, resulting in larger distances between resource extraction, manufacturing, and distribution facilities (McKinnon 2006). A significant reduction in transport activity is not likely to take place in the years to come. On the contrary, studies conducted by Piecyk and McKinnon (2010) show for the UK that current best practices like centralization of production and inventory as well as the relocation of production capacity to other countries are expected to proceed until 2020 and beyond. These strategies together with operational best practices like the increased use of online retailing, global sourcing and product-returns have considerable effects on a company’s distribution network and, hence, transport activities.

One of the big side effects of increased transport activities are emissions. The combustion of fossil fuels releases greenhouse gases into the atmosphere contributing to further global warming. In accordance with the Kyoto Protocol, six different gases are subsumed under the term greenhouse gases with carbon dioxide (CO2) accounting for 84% of greenhouse gas emissions in the European Union in 2005. Other greenhouse gases like methane (CH4) and nitrous oxide (N2O) account for only a minor share of approximately 7% respectively (EEA 2009). In total, the transport sector is responsible for almost 20% of greenhouse gases emitted in the EU27 in 2006, which makes it the second biggest polluter after the energy industries. Almost 93% of greenhouse gas emissions from transport activities stem from transportation on road, making it the predominant mode not only in terms of tonne-km but also in terms of greenhouse gas emissions (Eurostat 2009).

The issue of environmental damage has long been neglected by companies. Even though the topic has been on the agenda of governments for a long time, the main interest for companies has been economic performance, paying no or little attention to the impact of their operations on the environment. However, this attitude is slowly changing and companies are starting to concentrate increasingly on the implications they have on the environment. According to Simchi-Levi (2010) three main reasons for this development can be identified. First, today’s consumers are more aware of the products they buy, considering also issues like “Fair Trade” or minimal environmental damage. Consequently, consumers are more and more demanding "green products". Second, companies usually associate high emissions with inefficiencies in their operations. Through the reduction of inefficiencies it is often assumed that environmental impacts are reduced as a positive side effect. The third reason mentioned by Simchi-Levi (2010) as well as Wu and Dunn (1995) is the need to comply with environmental regulations from governments and organizations. National as well as international governments (especially the European Union) have already introduced different environmental regulations in order to reduce emissions or to protect the environment in general. Examples of regulations in this respect are manifold and include, for instance, vehicle emission standards, recycling requirements, or the EU ETS.

The EU ETS aims at reducing carbon emissions from manufacturing activities in certain energy intensive industries. However, activities associated with the distribution of products, i.e. transportation and warehousing activities, are not part of the EU ETS or other strict environmental regulations with respect to greenhouse gas emissions. But this situation is expected to change in the near future (see, for example, European Commission 2009, 2011). There are several ways of imposing environmental regulations on distribution activities, but the main focus currently lies on regulations concerning greenhouse gas emissions from transport. The most discussed topics in this respect are usually associated with increased costs for companies (Aronsson and Huge-Brodin 2006) and include the taxation of greenhouse gas emissions (see, for instance, Piecyk and McKinnon 2007) or the inclusion of transportation into the EU ETS (see, for example, Department for Transport 2009). But with no such regulations in force at the moment, the companies' objectives are the optimization of costs or other economic criteria, leaving the environmental effects of their decisions completely out of scope. Consequently, also decisions concerning the design of a company's distribution network focus on the improvement of economic performance only. Yet, network decisions are crucial for the environmental performance, since they also determine the necessary transport activities in a network.

3 Facility location models and environmental extensions

The structure of a company's distribution network is of vital importance since it provides the basis for competitiveness but also involves considerable costs and emissions. In this respect, decisions concerning the number, location, and capacity of warehouses are highly relevant. Furthermore, different trade-off situations can occur and must be considered in decision making. Trade-offs exist for example between operational costs and customer service or between transport costs and inventory costs (Wu and Dunn 1995; Chopra and Meindl 2010). As soon as environmental aspects are concerned, further trade-offs must be considered. While, for instance, a rather centralized distribution network results in an increasing volume of transport activities on the outbound side, inbound transport activities are expected to be reduced. This leads to a trade-off between emissions from inbound and outbound transportation.

Distribution network design decisions are usually strategic in their nature, meaning that they have a long-lasting effect for the company. In this context, decisions include the number, location, and capacity of warehouses and manufacturing plants as well as the flow of materials in the network (Simchi-Levi et al. 2008). In this regard, location decisions are often assumed to be the most critical and most difficult decisions, as they form the basis for further decisions in the supply chain like vehicle routing decisions or inventory decisions (Daskin et al. 2005).

Decisions concerning the location of facilities are usually supported by mathematical models, so called facility location models, which can be implemented in different software tools. A facility location model usually involves a set of customers and a set of potential facilities to serve these customers. With the help of these models it is possible to determine which facilities should be in operation and which customer should be served from which facility in order to achieve a certain objective. The majority of models aim at finding the network which leads to least costs. Only limited work is available on the maximization of profit. The number of models using multi-objective optimization is small at the moment, but is expected to grow steadily in the years to come (Melo et al. 2009).

Mathematical models for the determination of optimal facility locations are manifold. Depending on the approach, the model integrates different characteristics like capacities of facilities or fixed charges for the operation of facilities. Furthermore, a model is characterized by the covered time horizon, the number of products, and the types of facilities under consideration. Whether some of the included components in the model are stochastic or deterministic is another criterion in order to classify different modeling approaches. The models are usually formulated as linear problems, nonlinear problems or mixed integer problems and solved using either general solvers or specific algorithms, leading to either exact or heuristic solutions. For a thorough analysis of facility location models see Melo et al. (2009) and the references therein.

Until recently, limited awareness has been given to the incorporation of environmental criteria into facility location models. Although this topic has received a growing awareness in the past years (Guillén-Gosálbez and Grossmann 2009), numerous publications focus on other issues of supply chain management like inventory decisions, lot sizing decisions, production planning decisions, or transport planning decisions (see, for example, Bonney and Jaber 2010, Benjafaar et al. 2010, Hoen et al. 2010 and Quariguasi Frota Neto et al. 2009). In the context of facility location models with environmental concerns, Diabat and Simchi-Levi (2009) present a model to determine the cost optimal manufacturing and distribution network, given a certain upper limit for CO2 emissions. Their work is extended by Abdallah et al. (2010) who additionally take into account decisions on green procurement. Hugo and Pistikopoulos (2005) develop a multi-objective mixed integer linear program for a supply chain in the chemical industry. Through optimal location and allocation decisions, the maximization of the net present value as well as the minimization of the environmental impact of the whole network is achieved. By balancing the environmental criteria against the traditional economic criteria, they discover a trade-off between the two that must be considered in decision making. A similar approach is chosen by Bojarksi et al. (2009) as well as Wang et al. (2011) who also use a multi-objective mixed integer linear program to consider economic and environmental issues in facility location and distribution planning. Guillén-Gosálbez and Grossmann (2009) extend the model of Hugo and Pistikopoulos (2005) and develop a bi-criterion stochastic non-linear mixed integer program in order to highlight the trade-offs between economic and environmental performance.

Environmental criteria can be incorporated into facility location models in different ways, depending on the availability of data. One way is to calculate a single environmental indicator to combine different environmental impacts and present them summarized into one figure. Several indicators exist in literature; one example is the Eco-Indicator 99 that is used by Hugo and Pistikopoulos (2005) and Guillén-Gosálbez and Grossmann (2009). However, another commonly suggested method of integrating environmental aspects is to calculate, estimate, or measure greenhouse gas emissions caused by operations (Aronsson and Huge-Brodin 2006). Although the determination of emissions can be complex for some operations, it can be done easily for transport operations (especially carbon dioxide and other greenhouse gases). In fact, there are two approaches for estimation (McKinnon and Piecyk 2010):

- Energy-based approach – the combustion of fossil fuel leads to the emission of greenhouse gases. Especially the emissions of carbon dioxide are directly proportional to the amount of fuel that is used. For truck transportation, the fuel usage of certain transport operations can be directly converted into CO2 emissions by applying a standard emission factor. Whether or not transportation on rail incurs direct emissions depends on the type of rail that is used. In the European Union, half of the rail network is electrified, whereas 50% of the network still uses diesel-powered railcars. In order to appropriately and completely estimate emissions from rail transportation also indirect emissions from the generation of energy must be considered. The intensity of indirect emissions strongly depends on the technology used for producing electricity and differs between countries (Uherek et al. 2010).

- Activity-based approach – if energy data on fuel used (for road transportation) or kilowatt hours (for rail transportation) is not available, estimations can be properly done through converting transport activities in terms of tonne-km into carbon emissions by using conversion factors. These conversion factors must take into account the amount of empty-running and the average load factor of the vehicles.

Carbon emissions are a straightforward instrument to obtain a rough overview of the environmental impact of operations. This holds particularly true when transportation is the main focus of analysis, which is the case in strategic facility location decisions. Thus, greenhouse gases are an appropriate measure of environmental performance. The analyses that are conducted with environmentally extended facility location models allow, for instance, the comparison of emissions from a cost optimal network design and a network where emissions are minimized. A comparison like this is of special interest since a cost optimal design does not necessarily correspond to the environmentally friendliest network design (Harris et al. 2011). It must also be kept in mind that, due to the long-term (i.e. strategic) nature of facility location decisions, some information might not be available at the time of decision making. As an example, concrete information about future environmental regulations with respect to greenhouse gas emissions from transportation is not available at the moment. Nevertheless, different possible regulations, like for example emission caps, emission trading, or emission taxes, should already be considered when making facility location decisions. Regulations like the ones mentioned usually add additional costs to the objective function of models and, thus, transform environmental criteria into economic ones (see, for example, Abdallah et al. 2010 and Diabat and Simchi-Levi 2009). By comparing different network design scenarios an assessment of different regulations with respect to costs as well as to environmental aspects is possible.

In the following section we present a model for facility location decision support that assesses costs and greenhouse gas emissions at the same time and we apply it to a case study from the petrochemical industry. Instead of analyzing all possible network design options we focus on selected distribution network scenarios that are analyzed in more detail. By comparing these few scenarios the impact of different network designs on economic and environmental performance can be compared easily. Furthermore, the economic and environmental effects of a possible future regulation, namely costs on carbon emissions, are analyzed. Due to the simplicity of the model, further regulations like emission caps or emission trading can be incorporated into the model rapidly, but this has not been done in this work.

4 A case study from the petrochemical industry

In the EU25, companies in the chemical industry are responsible for 1,500 million tons of freight each year, whereby the most predominant mode of transport in terms of tons-lifted is road, accounting for almost 90% of chemical sales in 2001 (Braithwaite 2005). Especially McKinnon (2004) and McKinnon (2005) present the importance of transport in the chemical industry over longer distances and base their arguments on the increased number of cross-border sales within the EU. Whereas sales within one member state of the EU were 55% in 1993, they decreased to 25% in 2003. In the same period of time cross-border sales within the EU increased drastically, from 27% to 46%. The remainder was traded outside the EU. McKinnon (2005) also emphasizes that logistics are quite significant sources of costs in (petro-)chemical supply chains and are, therefore, more and more the center of attention when companies think of cost reduction.

In the following case study we take a close look on the distribution network of one of the leading petrochemical companies in Southeastern Europe. Being aware of the constant market pressure from other international companies the company in scope aims at reducing the costs of distribution in the considered region, primarily through reducing the number of local storage locations. Figure 1 depicts the current distribution network of the company. Crude oil is either exploited from domestic oil fields or offshore oil rigs or it is imported from other oil producing countries. Afterwards, the crude oil is directly transported to a single refinery by pipeline or train for further processing. In the refinery the crude oil is transformed into several final products. In the course of this paper, the analysis concentrates on fuel, meaning gasoline and diesel products. For the purpose of simplification we make no differentiation between these two products. After processing, the fuel is transported to 21 storage locations spread across the region in accordance with the demand in the surrounding area. Inbound transportation to the storage locations (primary transport) is carried out by rail; there is only one storage location that possesses a direct connection to the refinery via pipeline. From the storage locations the fuel is further transported by truck to the company's own filling stations in 276 cities (secondary transport).

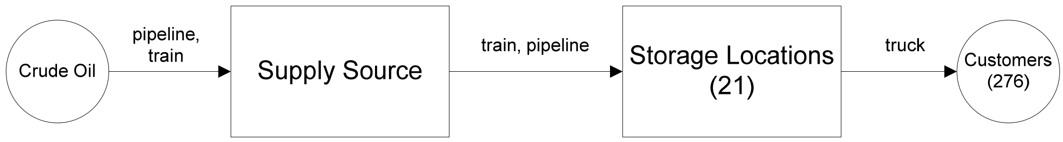

***Figure 1**: Distribution network overview*

The analyses concentrate on different network scenarios with an altering number of storage locations and the corresponding effects on primary and secondary transportation. In the current situation the company aims at minimizing lead time from the storage locations to the filling stations. This is achieved by the spread of storage locations across the whole region. Through this highly decentralized distribution network the company obtains short secondary transport distances and a high service level at the same time, but only at high costs for the operation of storage facilities and primary transport. In order to reduce actual costs of distribution the company wants to reduce the number of storage locations with no negative impacts on lead time. For that purpose, a decision-support tool has been created. This tool enables the company to consider different distribution network designs and to compare total annual costs of different network scenarios. At the same time, the environmental effects of structural changes in the distribution network are assessed in the form of carbon emissions from primary and secondary transportation.

4.1 Modeling approach

The application of the decision-support tool should be at the same time self-explanatory and easy-to-use. Apart from that, changes of input parameters should be possible quickly and easily. In order to achieve this purpose we implemented the tool in the spreadsheet application Microsoft Excel with its Visual Basic for Applications (VBA) environment. All necessary data was provided by the company for a representative year.

We created a static and deterministic model with a covered time horizon of one year. In order to effectively link actual expert knowledge and optimization methods, the user of the tool must select those storage locations that should be in operation in a first step. Based on this decision, the tool calculates the total annual distribution costs of the network. Total annual distribution costs consist of primary transport costs, fixed and variable costs of operating storage locations, and secondary transport costs. We assume that there are no costs for the closure of storage locations. Non-recurring investment costs are also depicted if some storage locations are planned to undergo certain steps of revamping in the future. The exploitation, delivery as well as the processing of crude oil is not included in the analysis.

By assigning the whole demand for each city to the closest storage location in operation, secondary transport costs are minimized. Thus, each city is supplied from only one storage location, namely the closest one. Based on this assignment, the tool calculates the amount of fuel that must be held in stock at each storage location as well as the associated operational costs and primary transport costs. Based on the amount and distance the product travels, primary as well as secondary transport activities are calculated in terms of tonne-km for rail and road transportation. Using conversion factors the total emissions from primary and secondary transport are calculated in terms of CO2-equivalents (CO2e), taking into account assumptions on load factor, truck type, and empty running. The Finnish Environmental Institute (SYKE, http://www.ymparisto.fi/) provided the relevant conversion factors for this analysis. It has to be kept in mind that this paper focuses on transport emissions only, indirect emissions from the operation of storage facilities are not considered. Instead it is assumed that storing fuel needs the same amount of energy in all storage locations, independent of their size and capacity.

4.2 Analysis and results

We consider five scenarios in this paper. The scenarios differ only with respect to the number of operating storage locations in the network. Using the expertise of the company it has been decided which storage locations are in operation in the different network scenarios. The current situation is presented in the Baseline scenario, which means that all 21 storage locations are in operation. This scenario serves as a reference point for comparison. In Scenario 2 four storage locations are closed and only 17 storage locations remain in operation. In Scenario 3 and 4 there are eight and six storage locations, respectively. In these scenarios the storage facilities are strategically located in order to maintain the desired outbound lead time. A highly centralized network is demonstrated in Scenario 5 which consists of only three storage locations. These three storage locations are located within a radius of approximately 100 km and in close proximity to the supplying refinery. Since the model does not include any constraints on the capacity of storage locations even a network with only one storage facility would be technically feasible. However, the company strictly refuses a network with just a single storage location for several reasons, like, for instance, too high investment costs or the lack of possible alternatives in case of accidents or breakdowns. Table 1 summarizes the results of the economic and environmental analysis, relative to the Baseline scenario.

Based on the economic performance, a distribution network with six strategically located storage locations leads to minimum total distribution costs (Scenario 4). Up to 7.6% of total costs can be saved in comparison to the Baseline situation. This reduction in total distribution costs is mainly attributable to a reduction in operational costs. As can be seen in Figure 2, operational costs decrease with the number of storage locations due to reductions in fixed costs. Compared to the Baseline scenario, primary transport costs change only moderately when reducing the number of storage locations. One reason for that is the geographical position of the operating storage facilities which is strategically chosen to achieve the required outbound lead time. As a matter of fact, primary transport costs are quite insensitive to the number of storage locations. Only in the highly centralized network with three storage locations in operation (Scenario 5) primary transport costs drop significantly. The close proximity of these storage locations to each other and to the supply source is the reason for this drastic decline.

	Baseline	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*
Number of storage locations	**21**	**17**	**8**	**6**	**3**
Operational costs	100	86.7	71.9	59.1	40.0
Primary transport costs	100	100.2	97.9	94.2	48.8
Secondary transport costs	100	102.9	126.9	141.3	233.8
Total distribution costs	**100**	**95.5**	**95.0**	**92.4**	**93.7**
Primary emissions	100	98.4	93.0	90.4	35.6
Secondary emissions	100	106.7	161.8	192.7	385.4
Total emissions	**100**	**101.5**	**119.1**	**129.2**	**168.1**

Table 1: *Economic and environmental results of scenario analysis*

However, this high degree of centralization demands a high amount of secondary transport activities. In addition, the flexible and accurate planning of transport activities is necessary in order to keep up the actual delivery reliability, but this aspect is not considered in this paper. It can be generally stated that a reduction in the number of storage locations necessitates a higher amount of secondary transport activities. Therefore, Scenario 5 owes the biggest share of total cost to secondary transport. Whereas secondary transport accounts for 65% of total distribution costs in this scenario, it is only between 26% and 40% in the Baseline and the other scenarios. Through this drastic increase in secondary transport costs, the reduction in primary transport and operational costs is compensated completely.

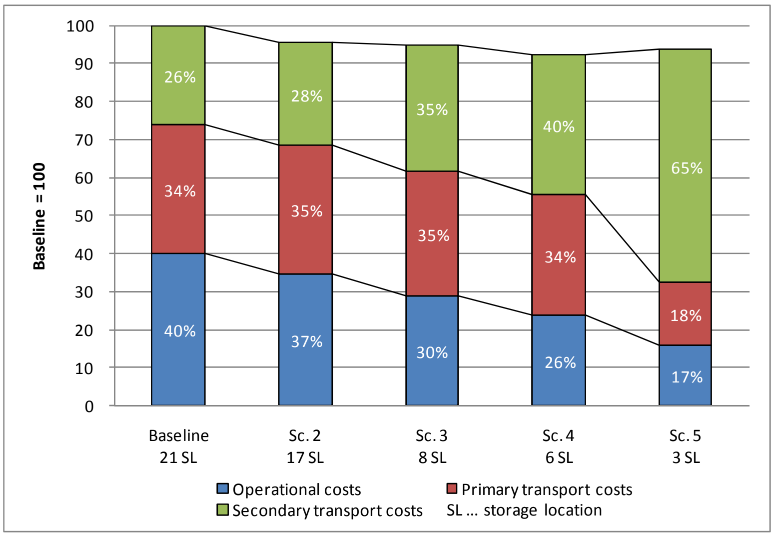

***Figure 2**: Total distribution costs*

The overall environmental performance of the different distribution network scenarios is graphically depicted in Figure 3. It shows the total transport emissions in terms of CO2e relative to the Baseline scenario. Total transport emissions in the distribution network are strongly dependent on the amount of truck transportation that is necessary. Because of its high carbon intensity compared to rail transportation, network scenarios with comparatively low truck transportation perform better with respect to environmental criteria. Consequently, the Baseline scenario with a high amount of primary rail transportation performs best in terms of carbon emissions compared to the other network scenarios. The more storage locations are closed, the more truck transportation is necessary, thus deteriorating environmental performance. With only three storage locations in operation the worst performance in terms of CO2e can be witnessed. Although primary transport emissions are at the minimum, the highly centralized network scenario results in secondary transport emissions that are almost four times higher than in the Baseline scenario.

When comparing total distribution costs and total transport emissions (Figure 4) the trade-off between these two criteria is obvious. Whereas the Baseline scenario with 21 operating storage locations results in the highest costs, it causes least emissions at the same time. The higher the degree of centralization, the more truck transport is necessary. Therefore, it can be concluded that reducing the number of storage locations increases total transport emissions in the distribution network. From an economic perspective, total distribution costs first decrease with the number of storage locations. However, at a certain degree of centralization reduced operational and primary transport costs can no longer compensate the increase in secondary transport costs. Thus, total distribution costs increase again.

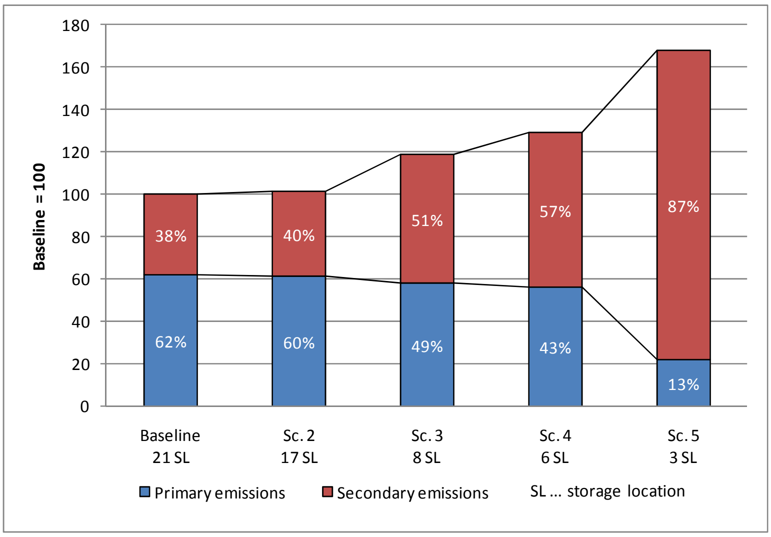

Figure 3: *Total transport emissions*

The analysis shows that the cost optimal network scenario causes the second highest emissions. A reduction in costs of approximately 7.6% is possible, but carbon emissions are more than 29% higher than in the Baseline situation. However, the figures above indicate that total distribution costs are quite stable around the cost optimal situation. It is, therefore, interesting to see that a deviation from the cost optimal situation (Scenario 4) does not lead to significant increases in total distribution costs, but reduces carbon emissions. For example, switching from a distribution network with six storage locations (Scenario 4) to eight storage locations (Scenario 3) increases total costs only slightly (about 2.8%) but the environmental performance improves, resulting in a reduction of carbon emissions of 7.8%.

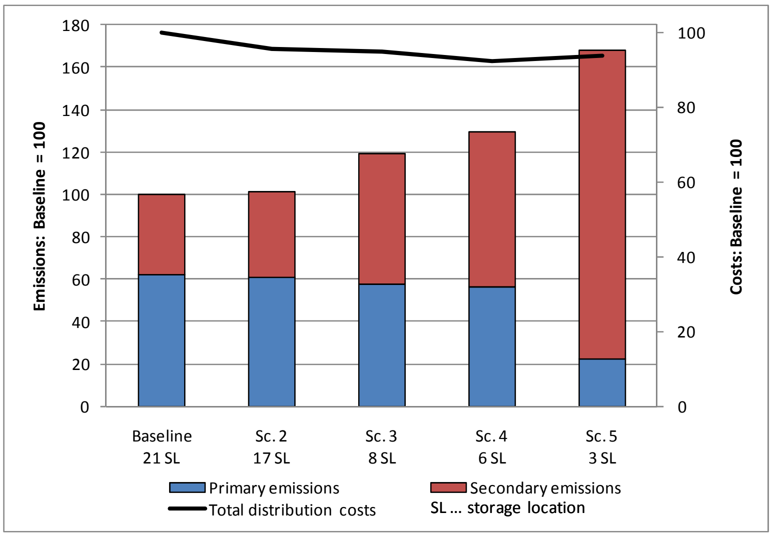

Figure 4: *Trade-off between total distribution costs and transport emissions*

Looking only at the economic performance of the different scenarios, companies may favor Scenario 4 with six operating storage locations. Consequently, the negative impact of this scenario on the environment is not considered in the decision-making. This attitude towards favoring economic before the environmental performance is still widely spread in companies today. Several reasons for this are possible; however, the most important one is that transport emissions currently do not have negative financial consequences for the company. There is an ongoing discussion about how to reduce carbon emissions from transport and which regulations are suitable for this purpose. One way is to impose costs on each ton of CO2e emitted through transport activity. Carbon costs are already effective in the EU ETS, where emission allowances can be purchased and sold on a carbon market. The actual costs for the right of emitting one ton of carbon emissions are determined by a market mechanism.

It is interesting to analyze how carbon costs would affect this case study, if they also applied to emissions from transportation. In that case, carbon emissions would have a direct influence on the total distribution costs. Therefore, we assume in our model that for each ton of CO2e emitted by transportation on rail or road the company is charged a certain amount of money. In this respect, this idea can be interpreted as a tax on carbon emissions that has to be paid per ton of CO2e emissions from transportation. By applying costs for carbon emissions, total distribution costs in all analyzed network scenarios increase (ceteris paribus). We conduct sensitivity analyses in order to determine the values of carbon costs at which the cost optimal distribution network becomes suboptimal. Scenario 2 with 17 storage locations is under close consideration in this respect, because of its potential for total cost reduction and only small increases in carbon emissions at the same time. This scenario incurs the second highest total distribution costs when a carbon tax is excluded. However, it performs second best as soon as cost for carbon emissions are included and more than €50 per ton are charged. The cost optimal network remains Scenario 4 with six storage locations in operation. But as soon as carbon costs exceed a critical value, the more decentralized Scenario 2 becomes the cost optimal situation. In this case study, carbon costs must exceed €170 per ton in order for the cost optimal network design to change. After that threshold, Scenario 2 stays optimal until the carbon tax amounts to €5,500 per ton. Only in that case the Baseline scenario with minimal emissions becomes cost optimal. For comparison, one can compare these figures with the costs of buying allowances for emitting CO2 under the EU ETS. In this regard, the price for emitting one ton of CO2 amounts to approximately €17 (on April 27, 2011). Consequently, this regulatory measure seems not to be appropriate for freight transportation.

5 Summary and conclusions

On the basis of a real world case study from the petrochemical industry in Europe, this paper shows the effects of changing the number of local storage locations on economic and environmental performance. Total costs of distribution are taken as an indicator for the economic performance, consisting of primary and secondary transport costs and fixed and variable operational costs in the operating storage facilities. As an environmental criterion, carbon emissions from rail and road transportation in terms of CO2e are considered. The economic as well as the environmental performance of different distribution network scenarios is determined with the help of a decision-support tool. The scenarios range from a highly decentralized network with 21 storage locations to a very centralized network with only three operating storage facilities.

The results of the analysis show that total distribution costs first decrease with the number of storage locations, but increase again when the number of storage locations is very small. This is due to increased secondary transport costs compensating reductions in operational costs and primary transport costs. From a cost perspective, operating six storage locations leads to minimal costs. The higher the degree of centralization, the more secondary transport activities on road are necessary, which increases carbon emissions. Thus, the environmental performance worsens with a decreasing number of storage locations. A trade-off between costs and emissions is evident in this case study. Whereas the most expensive network scenario results in least emissions, the cost optimal network leads to second highest emissions. It is interesting to see, however, that only a small deviation from the cost minimum situation does indeed not increase total distribution costs to a large extent; yet notable reductions in carbon emissions can be achieved by doing so.

Further analyses should, therefore, concentrate on the sensitivity of total costs in distribution networks with special focus on the respective consequences on carbon emissions. Moreover, the effects of different environmental regulations for transport should be assessed. Due to the relative simplicity of the underlying model caps on greenhouse gas emissions or an emission trading mechanism can be incorporated rapidly. Additionally, given the actual data from the company in consideration, a more sophisticated mathematical optimization model can be implemented taking into account several possible governmental regulations with respect to carbon emissions. Besides, additional information can be used to implement, for instance, the consequences of scale economies in storage locations, capacity constraints, or indirect emissions from storage locations.

References

Abdallah, T.; Diabat, A.; Simchi-Levi, D. (2010) A carbon sensitive supply chain network problem with green procurement. Proceedings of the 40th International Conference on Computers and Industrial Engineering, pp. 1-6

Aronsson, H.; Huge-Brodin, M. (2006) The environmental impact of changing logistics structures. The International Journal of Logistics Management 17 (3), pp. 394-415

Benjafaar, S.; Li, Y.; Daskin, M. (2010) Carbon footprint and the management of supply chains: Insights from simple models. Working Paper, University of Minnesota

Bojarksi, A.D.; Laínez, J.M.; Enspuna, A.; Puigjaner, L. (2009) Incorporating environmental impacts and regulations in a holistic supply chains modeling: An LCA approach. Computers and Chemical Engineering, 33 (10), pp. 1747-1759

Bonney, M.; Jaber, M.Y. (2010) Environmentally responsible inventory models: Non-classical models for a non-classical era. International Journal of Production Economics (In press)

Braithwaite, A. (2005) Maximising performance – the power of supply chain collaboration. EPCA, Cefic. http://www.cefic.org/Documents/IndustrySupport/Transport-and-Logistics/Maxi-mising-performance-the-power-of-supply-chain-collaboration-October2005.pdf

Chopra, S.; Meindl, P. (2010) Supply Chain Management - Strategy, Planning, and Operation, 4th ed., Pearson, Upper Saddle River

Daskin, M.S.; Snyder, L.V.; Berger, R.T. (2005) Facility location in supply chain design. In: Langevin, A.; Riopel, D. (eds.) Logistics systems: Design and optimization. Springer, New York, pp. 39-65

Department for Transport (2009) Road Transport and the EU Emission Trading Scheme. http://webarchive.nationalarchives.gov.uk/+/http://www.dft.gov.uk/adobepdf/165252/euemis traschemepdf

Diabat, A.; Simchi-Levi, D. (2009) A carbon-capped supply chain network problem. Proceedings of the 2009 IEEE IEEM, pp. 523-527

EEA (2009) Greenhouse gas emission trends and projections in Europe 2009. European Environment Agency

European Commission (2009) A sustainable future for transport – Towards an integrated, technology-led and user-friendly system. Publications Office of the European Union, Luxembourg

European Commission (2011) Roadmap to a single European transport area – towards a competitive and resource efficient transport system. White paper, Brussels

Eurostat (2009) Panorama of Transport. http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-DA-09-001/EN/KS-DA-09-001-EN.PDF

Golicic, S.L.; Boerstler, C.N.; Ellram, L.M. (2010) "Greening" transportation in the supply chain. MIT Sloan Management Review, 51 (2), pp. 47-55

Guillén-Gosálbez, G.; Grossmann, I.E. (2009) Optimal design and planning of sustainable chemical supply chains under uncertainty. American Institute of Chemical Engineers Journal, 55 (1), pp. 99-121

Harris, I.; Naim, M.; Palmer, A.; Potter, A.; Mumford, C. (2011) Assessing the impact of cost optimization based on infrastructure modelling on CO2 emissions. International Journal of Production Economics, 131 (1), pp. 313-321

Hoen, K.; Tan, T.; Fransoo, J.; van Houtum, G. (2010) Effect of carbon emission regulations on transport mode selection in supply chains. Working Paper, Eindhoven University of Technology

Hugo, A.; Pistikopoulos, E.N. (2005) Environmentally conscious long-range planning and design of supply chain networks. Journal of Cleaner Production, 13 (15), pp. 1471-1491

McKinnon, A. (2004) Supply chain excellence in the European chemical industry. Heriot-Watt University, Edinburgh

McKinnon, A. (2005) European chemical supply-chain: Threats and opportunities. Logistics and Transport Focus, 7 (3), pp. 30-35

McKinnon, A. (2006) Life without trucks: The impact of a temporary disruption of road freight transport on a national economy. Journal of Business Logistics, 27 (2), pp. 227-250

McKinnon, A.; Piecyk, M.I. (2010) Measuring and managing CO2 emissions in European chemical transport. Heriot-Watt University, Edinburgh

Melo, M.T.; Nickel, S.; Saldanha-da-Gama, F. (2009) Facility location and supply chain management - A review. European Journal of Operational Research, 196 (2), pp. 401-412

Piecyk, M.I.; McKinnon, A. (2007) Internalizing the external costs of road freight transport in the UK. Logistics Research Centre: Heriot-Watt University - Edinburgh

Piecyk, M.I.; McKinnon, A. (2010) Forecasting the carbon footprint of road freight transport in 2020. International Journal of Production Economics, 128 (1), pp. 31-42

Quariguasi Frota Neto, J.; Walther, G.; Bloemhof, J.; van Nunen, J.; Spengler, T. (2009) From closed-loop to sustainable supply chains: The WEEE case. International Journal of Production Research, 48 (5), pp. 4463-4481

Simchi-Levi, D.; Kaminsky, P.; Simchi-Levi, E. (2008) Designing and managing the supply chain, 3rd ed., McGraw-Hill/Irwin, New York

Simchi-Levi, D. (2010) Operations rules - Delivering customer value through flexible operations, The MIT Press, Cambridge, Massachusetts

Uherek, E.; Halenka, T.; Borken-Kleefeld, J.; Balkanski, Y.; Berntsen, T.; Borrego, C.; Gauss, M.; Hoor, P.; Juda-Rezler, K.; Lelieveld, J.; Melas, D.; Rypdal, K.; Schmid, S. (2010) Transport impacts on atmosphere and climate: Land transport. Atmospheric Environment, 44 (37), pp. 4772-4816

Wang, F.; Lai, X.; Shi, N. (2011) A multi-objective optimization for green supply chain network design. Decision Support Systems, 51 (2), pp. 262-269

Wu, H.J.; Dunn, S.C. (1995) Environmentally responsible logistics systems. International Journal of Physical Distribution & Logistics, 25 (2), pp. 20-38