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Facility location decisions with environmental considerations. A case study from the petrochemical industry

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Facility location decisions with environmental considerations

A case study from the petrochemical industry

The recently growing concerns of customers and governments about environmental protection and greenhouse gas reduction have forced companies to integrate the topic of environmental sustainability into their decision making. Facility location decisions are of special relevance in this respect because of their strategic nature. Furthermore, many different trade-offs must be considered, for example between operational costs and customer service. But as soon as environmental issues are concerned, other critical issues must be considered as well. Based on a case study from the petrochemical industry, this paper extends two basic facility location models and shows the impact of distribution network-design decisions on the economic and environmental performance of the company. The results show a trade-off between total (distribution) costs and transport carbon emissions.

1. Introduction

The topic of environmental sustainability in business processes has been on the agenda for several years. This has led to lots of research concerning the effects of certain operations on the environmental performance of a company (Seuring/Müller 2008). Because of the still growing concerns of customers and governments about environmental protection and the reduction of greenhouse gases, companies today are forced to integrate the topic of environmental sustainability into their decision making. Especially production processes in certain energy intensive industries are under closer investigation because they usually offer a certain potential for emission reduction and are, thus, enforced by national or international organizations, like the European Union (EEA 2009).

There are already different environmental regulations in force in the European Union, like the Waste Electrical and Electronic Equipment (WEEE) directive, regulations on the use of biofuels or the EU Emission Trading Scheme (ETS). The EU ETS aims at controlling the emissions from energy intensive processes by a cap-and-trade system. More than 10,000 industrial sites in Europe are participating in this market mechanism. Since 2012, also aviation is included and it is expected that further modes of transport will be included in the EU ETS (Kok/Gille 2009). But until now, distribution processes, in particular road and rail transportation as well as warehousing activities, are not yet subject to strict environmental regulations with respect to greenhouse gas emissions. Nevertheless, companies are well advised to concentrate not only on their economic, but also their environmental performance, when making supply chain decisions.

In this paper, we present a way of combining economic as well as environmental aspects when evaluating (strategic) distribution network-design decisions, in particular facility location decisions. We make use of two widely used models, namely the p-median problem and the Warehouse Location Problem and base our analysis on a real-world case study with one of the leading petrochemical companies in Southeastern Europe. The company in scope aims at restructuring its distribution network with a special focus on optimizing the number of local storage locations in the considered region. 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 transport activities. In a first step, we apply a p-median problem that is implemented in a decision-support tool. This tool allows the assessment of different network design scenarios with respect to total costs and transport carbon emissions and it makes intensive use of actual expert knowledge. In a second step, we propose and apply an "environmentally extended" Warehouse Location Problem to the case study and compare the results of the different models. Furthermore, we show the impact of a possible future regulation, namely the imposition of carbon costs, on the optimal network-design.

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 approaches and the results are described in detail in Section 4. Section 5 concludes this paper by pointing out further research opportunities.

2. Transport activities and transport emissions

In the European Union, freight transport is one of the most important and still growing economic sectors. In the last 15 years, transport activities increased on average 2.8% each

year in terms of tonne-km. Since transportation is no longer considered as a necessary evil but as a way of achieving competitiveness, current business practices like global sourcing, just-in-time manufacturing or centralization of production and warehousing rely heavily on transportation and, thus, favor increased transport activities (Golicic et al. 2010, Aronsson/Huge-Brodin 2006). It is not expected that a reduction in transportation will take place in the upcoming years. On the contrary, the current best practices together with increased online retailing and product returns are considered to proceed until 2020 and beyond (Piecyk/McKinnon 2010). Furthermore, the modes of transport as well as their respective usage keep changing. Road is the predominant transport mode (in terms of tonne-km) with a still growing share, while the proportion of rail and water navigation is declining steadily (OECD 2006).

Consequently, the transport sector is also responsible for emitting a considerable amount of greenhouse gases into the atmosphere, thereby contributing to further global warming. Especially carbon dioxide (CO_2) emissions from the combustion of fossil fuels in truck transportation are a significant source of greenhouse gases. In total, transportation is responsible for almost 20% of total greenhouse gas emissions in the European Union, making it the second largest polluting sector after the energy producing industries and the only sector that was not able to reduce its emissions compared to recent years (EEA 2009).

Because of the missing financial consequences, 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 their operations have on the environment for several reasons. One reason that is often mentioned in the literature is the need to comply with environmental regulations from governments and organizations (Simchi-Levi 2010).

Whereas there are already several regulations in force for certain industries or processes in a supply chain, activities associated with the distribution of products are not yet subject to 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/Huge-Brodin 2006) and include the taxation of greenhouse gas emissions (see, for instance, Piecyk/McKinnon 2007) or the inclusion of transportation into the EU ETS (see, for example, Holmgren et al. 2006). 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.

Decisions in a supply chain must be made on three different levels, namely on a short-term, mid-term and long-term level. Short- and mid-term decisions include, for instance, lot sizing decisions, inventory decisions or decisions concerning the choice of the most appropriate transport mode. Long-term, or strategic, decisions in a supply chain and in particular facility location decisions are considered as the most crucial decisions, since they determine the structure of a company's distribution network. Decisions in this context usually have long-lasting effects, are associated with high costs and form the basis for further decisions in the network, for instance the allocation of demand or vehicle routing considerations (Simchi-Levi et al. 2008, Daskin et al. 2005). Usually, decisions in this respect focus on the improvement of economic performance only. Yet, network decisions are crucial for the environmental performance as well, 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/Dunn 1995; Chopra/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.

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, different types of models can be distinguished. One of the most common and intensively studied problems in facility location is the p-median problem. In this type of uncapacitated problem, exactly p facilities have to be located and each customer is served from its closest facility. In contrast to that, the number of facilities to locate is a decision variable in Warehouse Location Problems. Additionally, fixed costs are present in this type of model (Scaparra/Scutella 2001). Furthermore, a model can be 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/Grossmann 2009), numerous publications focus on other issues of supply chain management like inventory decisions (Bonney/Jaber 2010), lot sizing decisions (Benjafaar et al. 2010), production planning decisions (Quariguasi Frota Neto et al. 2009) or transport planning decisions (Hoen et al. 2010, Bauer et al. 2010). In the context of facility location models with environmental concerns, Quariguasi Frota Neto et al. (2008) develop a framework for a sustainable logistics network and address the conflicting nature of the corresponding logistics costs and its environmental performance. They also stress the importance of using multi-objective optimization for highlighting this trade-off. Besides that, Diabat/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. In contrast to that, Hugo/Pistikopoulos (2005) develop a multi-objective mixed integer linear program for a supply chain in the chemical industry using Life Cycle Assessment criteria

together with the Eco-Indicator 99 methodology. 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/Grossmann (2009) extend the model of Hugo/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. Langella/Zanoni (2010) concentrate on eco-efficient network-design decisions taking into account product returns. They illustrate their approach through a case study and provide means for managers to choose between different solutions, thereby balancing costs and environmental criteria.

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 the literature; one example is the Eco-Indicator 99 that is used by Hugo/Pistikopoulos (2005) and Guillén-Gosálbez/Grossmann (2009), whereas Langella/Zanoni (2010) use the cumulative energy demand (CED). However, another commonly suggested method of integrating environmental aspects is to calculate, estimate or measure greenhouse gas emissions caused by operations (Aronsson/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/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 CO_2 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 warehouse 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,

indicating a trade-off between these two measures (Harris et al. 2011). It is one of the goals of this work to highlight this trade-off between environmental and economic performance. Although several authors already demonstrated this conflicting situation, the models that are used are rather complex and often difficult to apply to real world situations. As already indicated by Benjafaar et al. (2010) there is a need for model-based research, extending classical models to also include environmental considerations in addition to the classical economic objectives. By doing so, the strong connection between operations in a company and their environmental consequences can be addressed, using simple and widely used models. We show our approach on two different models. First, we extend the classical p-median problem by integrating environmental considerations in terms of CO_2 emissions from transport activities. For that purpose, we create a decision-support tool in Microsoft Excel to support decision makers and illustrate the economic as well as environmental results. This tool provides two kinds of solution approaches, an exact one using a standard solver and a heuristic one, allowing the integration of expert knowledge and making it, thus, especially viable for the user. Second, we analyze the classical Warehouse Location Problem with environmental extensions. These two models are widely used in strategic facility location analysis and provide a solid basis for further analyses on a higher level of detail. Both models are then applied to a case study from the petrochemical industry in order to show their applicability and the resulting trade-offs on a real-world example.

It must 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/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 with our extended models.


4. A case study from the petrochemical industry

In the EU25, companies in the chemical industry are responsible for 1.5 billion tons of freight each year. The most predominant mode of transport in terms of tonnage 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 processes are quite significant sources of costs in (petro-) chemical supply chains and become 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. Because of the increasing pressure from other international companies, the focal company tries to reduce its costs of distribution. The current distribution network of the company is depicted in Figure 1. Crude oil is either exploited directly or it is imported from other oil producing countries and transported to a

single refinery by pipeline or train for further processing. In the refinery the crude oil is transformed into several final products, but we focus our analysis on fuel, meaning gasoline and diesel products, and make no differentiation between these two products. The processed fuel is then transported to 20 storage locations (or warehouses, depots) spread around the region in accordance with the demand in the surrounding area. Inbound transportation from the refinery to the depots (primary transport) is carried out mainly by rail. There exists only one depot that has a direct connection to the refinery via pipeline. From the storage locations the fuel is further transported to the company's own filling stations in 276 cities. This secondary transport is carried out by truck only.

Fig. 1: Distribution network overview
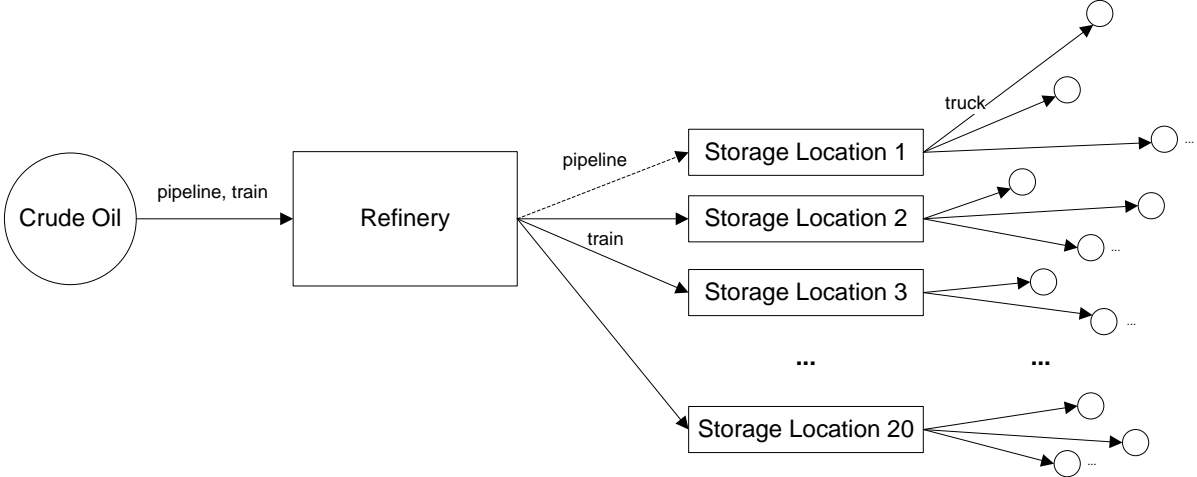
In the current situation the company aims at minimizing lead time from the storage locations to the filling stations. This is achieved by the spread of storage locations across the whole region. Through this highly decentralized distribution network the company obtains short secondary transport distances 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. Currently, the filling stations order fuel directly from their assigned storage location and receive it two days later. This delivery lead time can still be reached even with less storage locations operating, since the distances between the depots and the filling stations are not too large. However, the fuel must be duly available in the respective depot, which requires improved planning and scheduling processes. Assuming that this is granted, the company should be able to achieve the current lead time even with less storage locations. Consequently, the influence of the network structure on the lead time to the filling stations will be negligible.

Furthermore, the effects of changing the distribution network design on the environmental performance should be evaluated in addition to the economic performance. For that purpose, a decision-support tool has been created, where the p-median problem is implemented. This tool enables the company to consider different distribution network-designs and to compare the total annual costs and the emissions from primary and secondary transportation in different network scenarios. This approach is described in the following section. Afterwards, the application of the environmentally extended Warehouse Location Problem to the case study is described.

4.1. Modeling approach for the p-median problem

In the p-median problem, exactly p facilities have to be located in order to fulfill customers' demand. The facilities do not differ from each other concerning the type of service they provide or their capacities. In particular, there are no capacity constraints in the p-median problem, making it an uncapacitated multi-facility problem (Azarmand/Jami, 2009). Each customer is always supplied from its closest facility. In the context of the case study, this means that each filling station is supplied solely from the depot located closest to it. Slightly adopting the notation of Scaparra/Scutella (2001, see Table 1), the classical p-median problem can be formulated as follows.

$$min: \sum_{j \in J} w_j \sum_{i \in I} d_{ij} x_{ij} \tag{1}$$

$$\sum_{i \in I} x_{ij} = 1 \qquad\qquad \forall j \in J \tag{2}$$

$$y_i - x_{ij} \geq 0 \qquad\qquad \forall i \in I, j \in J \tag{3}$$

$$\sum_{i \in I} y_i = p \tag{4}$$

$$x_{ij}, y_i \in \{0,1\} \qquad\qquad \forall i \in I, j \in J \tag{5}$$

Equation (1) minimizes the sum of distances from each customer to its closest facility, weighted by the total demand of the customer. Equations (2) ensure that all demand is fulfilled. Constraints (3) allow a customer only to be served from an open facility, while Constraint (4) limits the number of open facilities to p. Constraints (5) define the variables of the model.

Tab. 1: Notation of the p-median model

$I = \{1, \dots n\}$	set of candidate facility locations
$J = \{1, \dots m\}$	set of filling stations
w_j	demand for the service of filling station j
d_{ij}	distance between filling station j and location i
x_{ij}	fraction of customer j's demand supplied from location i
y_i	binary decision variable, 1 if location i is established, 0 otherwise
p	number of facilities to locate

In the context of this case study, the p-median problem minimizes secondary tonne-km from the warehouses to the filling stations, replenishing each filling station from its closest operating storage location. Since the number of operating location is fixed to p, this type of problem allows the analysis of different network scenarios and is very suitable to be implemented in a decision-support tool. Relevant data for a representative year has been provided by the company. In particular, this data includes information on the locations of filling stations, the existing warehouse locations, demand data but also information about primary and secondary transport processes as well as fixed and variable operational costs in the warehouses. Based on the solution of the model concerning which locations should be in operation, the total annual distribution costs of the resulting network are calculated. Total annual distribution costs consist of transport costs as well as fixed and variable costs of operating storage locations. We assume that there are no costs for the closure of storage

locations. The exploitation, delivery and the processing of crude oil is not included in the analysis.

Transport costs in the network arise for primary and secondary transport and are dependent on the distance, the mode and the amount of fuel that is transported. Operational costs in the operating warehouses consist of a fixed and a variable part. Variable operational costs are mainly electricity costs for pumping fuel in and out of the tanks, while fixed operational costs include costs for personnel and maintenance but also depreciation and repair work.

The model is extended to also include CO_2-equivalent (CO_2-e) emissions from primary and secondary transport activities for pipeline, rail and road transportation. This is done in two steps, first the transport activities in terms of tonne-km are calculated for each mode of transportation. Second, the corresponding transport emissions are calculated by an activity-based approach as described above. In particular the conversion factors that are used are provided by Bauer et al. (2011) and take into account information about the load factor (85% for trucks, 95% for trains), the truck and train type used (EURO V trucks and electrified full-trains), as well as information on empty running (50% for trucks and trains, respectively). It has to be kept in mind, however, 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.

Concerning the way of solving the model, two distinct approaches have been chosen. On the one hand, the model is implemented in Microsoft Excel using all relevant data and solved exactly using CPLEX and its Excel Connector. This allows for an exact solution in reasonable time, given the size of the problem. On the other hand, we tried to also find a way of integrating actual expert knowledge into the model in some way, accepting that the solution found may not be the optimal one. Therefore, we developed a decision-support tool which the focal company can use for further analyses on the basis of the p-median model, but which requires certain input from its users. The tool works in two steps. First, the user of the tool must select those warehouses that should be in operation. Based on this decision, the tool calculates the total annual distribution costs of the network in a second step, given that all filling stations are replenished from their closest operating storage location, as it is the case in the p-median problem. It is important that the application of this tool is at the same time self-explanatory and easy-to-use. Apart from that, changes of input parameters should be made possible in a quick and easy way. In order to achieve this purpose, we implemented this tool in Microsoft Excel with its Visual Basic for Applications (VBA) environment. It must be noted that this tool does not prove optimality of a certain network-design because the operating locations are selected by the user. Instead, the approach can be interpreted as a heuristic way of finding (near) optimal solution within shortest time by effectively linking actual expert knowledge and optimization methods. In the following subsection, the results of both solving procedures are briefly discussed.

4.2. Analysis and results of the p-median problem

For both the heuristic as well as the exact solution several scenarios have been considered in the course of the analysis. In particular, we focus on five scenarios which differ with respect to the number of operating storage locations in the network. Which storage locations to operate is determined automatically in the exact solution, whereas experts from the company decided which storage locations are in operation in the different network scenarios when using the heuristic approach. The current situation is presented in the Baseline scenario, which means that all 20 storage locations are in operation. This scenario serves as a reference point for comparison and all further results are normalized to this scenario because of

confidentiality issues. In Scenario 2, four storage locations are closed and only 16 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 p-median problem 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.

For all five scenarios the economic and environmental results are calculated using the heuristic solution in the decision-support tool and the exact model. Interestingly, the results are the same in all but two scenarios, in which the difference is only marginal. Except for Scenarios 2 and 3 the experts agreed to operate the same storage facilities as were found to be optimal by the p-median model. In these two exceptions, the experts decided on one and two different warehouses to operate, respectively, ye the results differ only marginally. Table 2 summarizes the results of the analysis, relative to the Baseline scenario. Only where there was a difference between the results of the heuristic and the exact solution (Scenario 2 and 3), a distinction has been made in the table and the following figures. It is interesting to see, however, that for Scenario 3 the heuristically obtained solution performs better in terms of total distribution costs than the exact solution. This is due to the p-median model minimizing secondary transport costs which are, in fact, smaller than in the exact solution for eight operating storage locations. Yet, primary transport costs and total distribution costs for this particular scenario are slightly higher.

Based on the economic performance, a distribution network with six strategically located storage locations leads to minimum total distribution costs (Scenario 4). Up to 24.9% 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. Figure 2 depicts the economic results graphically, the total distribution costs of all scenarios being normalized to the Baseline scenario. Furthermore, the shares of transportation and operational costs are shown as percentage of the scenario's respective total distribution costs. As can be seen, 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 whereas secondary transport costs increase intuitively. The close proximity of these storage locations to each other and to the refinery is the reason for that.

Tab. 2: Economic and environmental results of scenario analysis

	Baseline	Sc. 2-h (heuristic)	Sc. 2-ex (exact)	Sc. 3-h (heuristic)	Sc. 3-ex (exact)	Sc. 4	Sc. 5
Storage locations	**20**	**16**	**16**	**8**	**8**	**6**	**3**
Operational costs	100	82.7	82.7	48.1	48.1	39.5	26.5
Primary transport costs	100	101.2	100.9	96.1	97.2	94.1	49.0
Secondary transport costs	100	103.1	102.1	123.0	122.9	134.6	232.4
Total distribution costs	**100**	**92.2**	**91.9**	**77.6**	**77.8**	**75.1**	**77.5**
Primary emissions	100	99.3	100.5	91.5	95.7	89.3	35.1
Secondary emissions	100	109.3	106.3	164.3	163.1	195.2	436.1

Total emissions	100	102.8	102.5	116.9	119.2	126.2	175.0

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 64% of total distribution costs in this scenario, it is only between 22% and 39% 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.
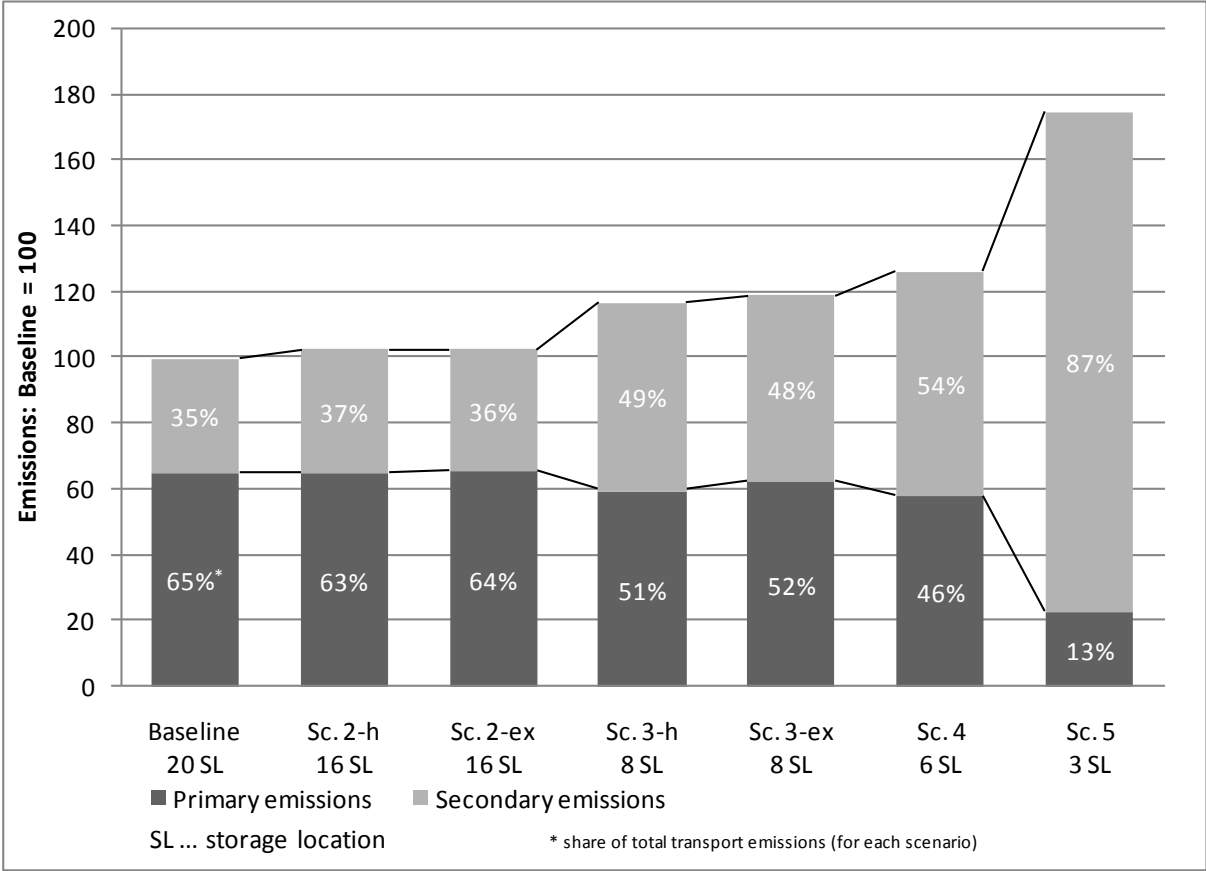
Fig. 2: Total distribution costs
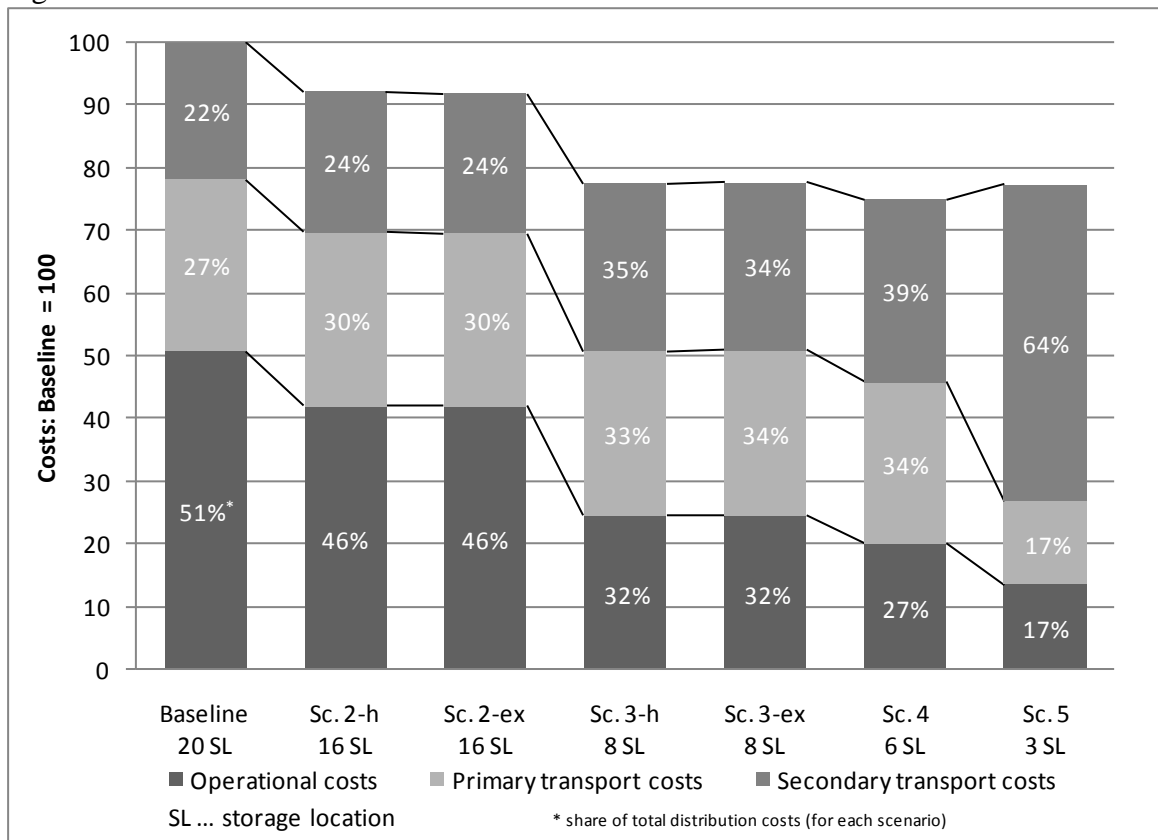
The overall environmental performance of the different distribution network scenarios is graphically depicted in Figure 3. It shows the total transport emissions of the different scenarios in terms of CO2-e, relative to the Baseline scenario. Furthermore, the share of primary and secondary transport emissions of the total transport emissions in a scenario is depicted as well. 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 CO2-e can be witnessed. Although primary transport emissions are at the minimum, the

highly centralized network scenario results in secondary transport emissions that are more than four times higher than in the Baseline scenario.

Fig. 3: Total transport emissions

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 20 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.

The analysis shows that the cost optimal network scenario causes the second highest emissions. A reduction in costs of approximately 25% is possible, but carbon emissions are more than 26% 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 2.5%) but the environmental performance improves, resulting in a reduction of carbon emissions of 9.3%.

Fig. 4: Trade-off between total distribution costs and transport emissions
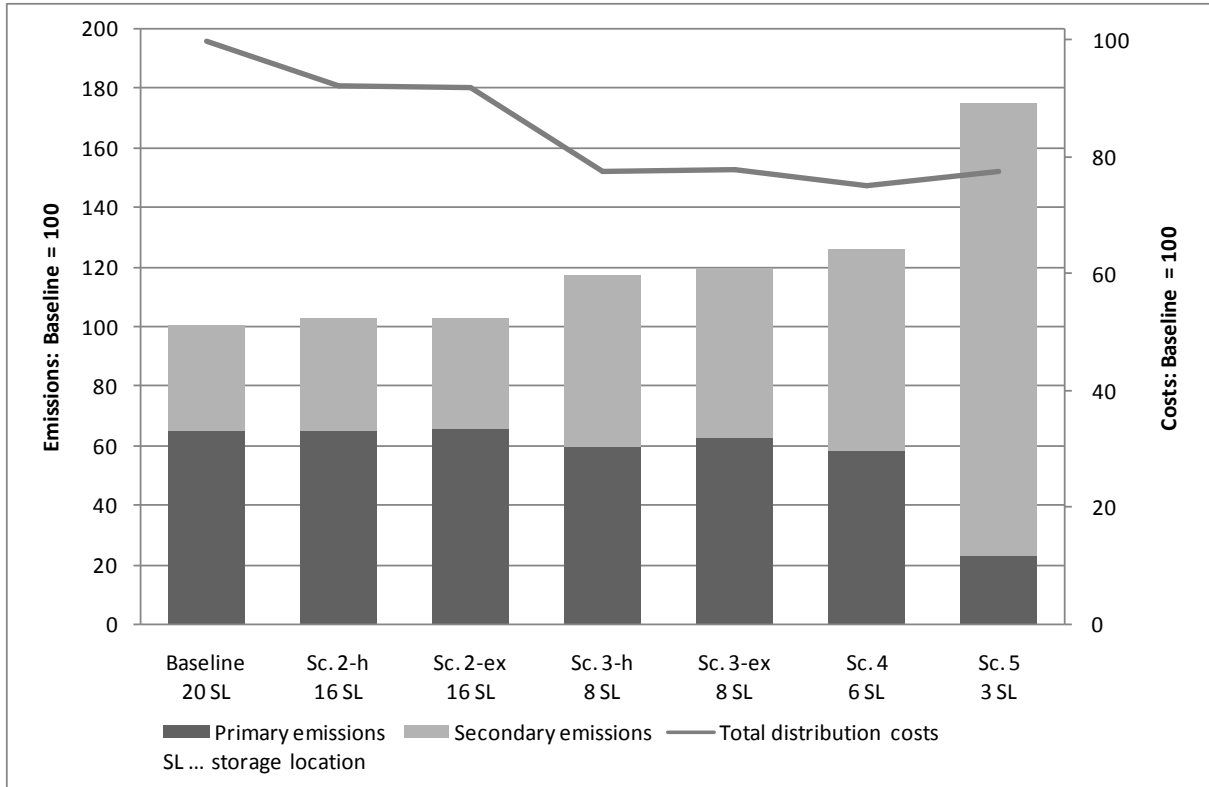
4.3. *Modeling approach for the Warehouse Location Problem*

In the capacitated Warehouse Location Problem not only the transport costs but also fixed and variable costs for the operation of facilities are considered in the optimization as well as capacity restrictions in these facilities. Furthermore, the number of facilities to operate is a decision variable. In the context of this case study, we now aim at minimizing total distribution costs, consisting of secondary transport costs and fixed operational costs as well as variable operational costs and primary transport costs.

The model can be formulated as a mixed integer program, its notation summarized in Table 3. I is the set of storage locations or depots and J is the set of filling stations. The binary variable y_i is set to 1 if storage location i is in operation. Otherwise it is 0. Variable x_{ij} determines the quantity of fuel shipped from storage location i to filling station j. Additionally, the variable x_{0i} is introduced, determining the quantity of fuel shipped from the refinery to storage location i. Each storage location has a maximum capacity C_i of annual throughput and fixed costs of f_i occur if the storage location is in operation. In the storage locations, variable operational costs v_i occur depending on the energy use per ton of fuel that is handled in storage location i. The filling stations have stationary and deterministic demand D_j. Primary transport costs per ton from the refinery to storage location i are denoted c_{0i}, whereas secondary transport costs per ton from storage location i to filling station j are denoted c_{ij}.

Tab. 3: Notation of the Warehouse Location Problem

$I = \{1, \dots n\}$	set of candidate facility locations
$J = \{1, \dots m\}$	set of filling stations
y_i	binary decision variable, 1 if location i is established, 0 otherwise
x_{ij}	quantity shipped from location i to customer j
x_{0i}	quantity shipped from the refinery to storage location i

C_i	capacity of storage location i
f_i	fixed costs for storage location i
v_i	variable operational costs at storage location i
D_j	demand at filling station j
c_{0i}	primary transport costs from the refinery to storage location i
c_{ij}	secondary transport costs from storage location i to filling station j
d_{0i}	distance from the refinery to storage location i
d_{ij}	distance between storage location i and filling station j
cf_p	conversion factor for primary transport emissions
cf_s	conversion factor for secondary transport emissions
E	total amount of transport emissions

For the calculation of the environmental impact, the following data is needed. Distance from the refinery to the storage locations is d_{0i} and the distance from storage location i to filling station j is denoted d_{ij}. Tonne-km can be determined with this information and are converted into CO2-e emissions using conversion factors cf_p for primary transportation and cf_s for secondary transportation. The total amount of CO2-e emissions is indicated by E.

The capacitated Warehouse Location Model can then be formulated as follows.

$$min: \sum_{i \in I} c_{0i} x_{0i} + \sum_{i \in I, j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i y_i + \sum_{i \in I, j \in J} v_i x_{ij} \qquad (6)$$

$$\sum_{i \in I} x_{ij} = D_j \qquad \qquad \forall j \in J \qquad (7)$$

$$\sum_{j \in J} x_{ij} = x_{0i} \qquad \qquad \forall i \in I \qquad (8)$$

$$C_i y_i \geq \sum_{j \in J} x_{ij} \qquad \qquad \forall i \in I \qquad (9)$$

$$E = cf_p \sum_{i \in I} d_{0i} x_{0i} + cf_s \sum_{i \in I, j \in J} d_{ij} x_{ij} \qquad (10)$$

$$y_i \in \{0,1\} \qquad \qquad \forall i \in I \qquad (11)$$

$$x_{ij} \geq 0 \qquad \qquad \forall i \in I, j \in J \qquad (12)$$

Equation (6) is the objective function, minimizing primary transport costs, fixed and variable operational costs as well as secondary transport costs. Constraints (7) make sure that the delivery quantity to filling station j equals the demand in that filling station. Constraints (8) ensure that the quantity delivered from a storage location to all assigned filling stations equals the delivery quantity from the refinery to the storage location. Furthermore, the deliveries to the filling stations must not exceed the maximum throughput in storage location i. This is made sure of in Equation (9). The total amount of CO2-e emissions is calculated in Equation (10), using conversion factors on the primary and secondary tonne-km. The remaining constraints determine the variables of the Warehouse Location Problem.

4.4. Analysis and results of the Warehouse Location Problem

The model has been implemented in Microsoft Excel and solved exactly with CPLEX and its Excel Connector. Considering only the economic performance, it turns out that six storage locations are optimal and minimize total distribution costs. It is interesting to see that the optimal number of operating storage locations is the same in the p-median and the Warehouse Location Problem. Furthermore, five of these six locations that minimize total distribution costs are also the same in both models. The difference is only in the operation of one warehouse. Because of the high amount of secondary transport activities, transport emissions are high in the cost-optimal situation. The least emissions are caused in the Baseline scenario, where a large amount of transport is carried out by rail. This supports the results from the p-median problem. Table 4 summarizes the results of the economic and environmental analysis, relative to the Baseline scenario.

Tab. 4: Economic and environmental results of the Warehouse Location Problem

	Baseline	Optimum
Number of storage locations	**20**	**6**
Operational costs	100	39.5
Primary transport costs	100	72.1
Secondary transport costs	100	152.2
Total distribution costs	**100**	**72.95**
Primary emissions	100	67.2
Secondary emissions	100	241.0
Total emissions	**100**	**127.8**

Although the Warehouse Location Problem results in only one optimal solution, we wanted to analyze the sensitivity of the results for different network-designs. So we solved the problem again, but we fixed the number of operating warehouses (like we did in the p-median problem) in order to compare the results. In other words, we included Constraint (13) into the Warehouse Location Problem and solved it with different values for p in each calculation.

$$\sum_{i \in I} y_i = p \tag{13}$$

Figure 5 depicts the result, namely the minimum total distribution costs (diamonds) for any given number of operating storage locations in the network and the corresponding carbon emissions (squares), normalized to the Baseline scenario.

It is interesting to see that also in this situation, the total costs of distribution first decrease when the number of operating storage locations is reduced, but increase again as soon as the degree of centralization is too high. Furthermore, the conflicting nature of total costs and total emissions can be clearly identified again in this analysis. But it is also visible that total costs are quite stable around the cost minimal situation, so that a small increase in costs can correspond to a high reduction in carbon emissions. For instance, by switching from six to seven operating storage locations would mean an increase in total costs of only 1.19%, but carbon emissions can be reduced by 3.19%.

This trade-off can be shown even better by using multi-objective optimization. In this case, one objective function is the minimization of total distribution costs, while the second objective function is the minimization of total transport emissions. For that purpose, Equation (10) is reformulated as an additional objective function. Since it is, obviously, not possible to find one single solution that minimizes both objectives at the same time, the efficient

solutions have to be sought. A solution, in this context, is considered efficient, if it is not possible to improve one objective without deteriorating the other objective. The set of all efficient solution is referred to as being Pareto-optimal and forming the (Pareto-) efficient frontier (Ehrgott 2008). Especially for multi-objective combinatorial problems like the WLP, finding all efficient solutions may not always be possible. As soon as integrality constraints arise, only a subset of all efficient solutions, namely the supported solutions, can be reached (Caramia/Dell'Olmo 2008). This is also the case in this work. For a detailed review on multi-criteria optimization and the characteristics of Pareto-frontiers in different types of problems, see Ehrgott (2005) and the references therein.

For solving multi-objective optimization problems, one method that is commonly used is the epsilon-constraint method (Deb 2001). The idea is to reformulate the multi-objective problem into a single objective problem and to use the second objective as a constraint (see Bérubé et al. 2009 for details). In this case, we keep the cost minimizing objective function and use the emission minimizing objective as a constraint. We establish a granulated vector (ε) of scalars as emission constraints, ranging from the minimum emissions that could be achieved (with all warehouses in operation) to those emissions that are caused in the cost-minimized network (six warehouses in operation). In this case, we created a vector consisting of 165 scalars which are used sequentially as right-hand side for the emission constraint in the WLP. Consequently, the WLP is solved with the objective to minimize total costs, each time with a different upper bound for the emission constraint. The remaining constraints of the model remain unchanged and the model is solved to optimality in each run. Therefore, all solutions that are found by this approach are optimal for the cost-minimizing objective function, given the upper bound of the emission constraint. The resulting solutions are then compared to each other and the dominated solutions are removed. Eventually, the remaining solutions form the frontier that is depicted in Figure 6. It shows all possible non-dominated solutions for the given case study that can be found by the described approach. The results (costs and emissions) are depicted relative to the Baseline scenario which is represented as a square. Yet, given the size of the vector, only a part of the efficient solution can be obtained and it cannot be guaranteed that all the solutions are per se Pareto-optimal. Still, all the solutions that have been found are feasible and all these points can be reached by the company, meaning that for any given costs (emissions) in Figure 6, there exists no (found) network-design, where fewer emissions (costs) can be achieved. The decision maker now has the opportunity to decide which point on this frontier he wants to realize. Given the fact that minimizing total costs results in high emissions and minimizing emissions results in high costs, this trade-off must always be considered in facility location decisions.

Fig. 5: Trade-off between costs and carbon emissions in the Warehouse Location Problem
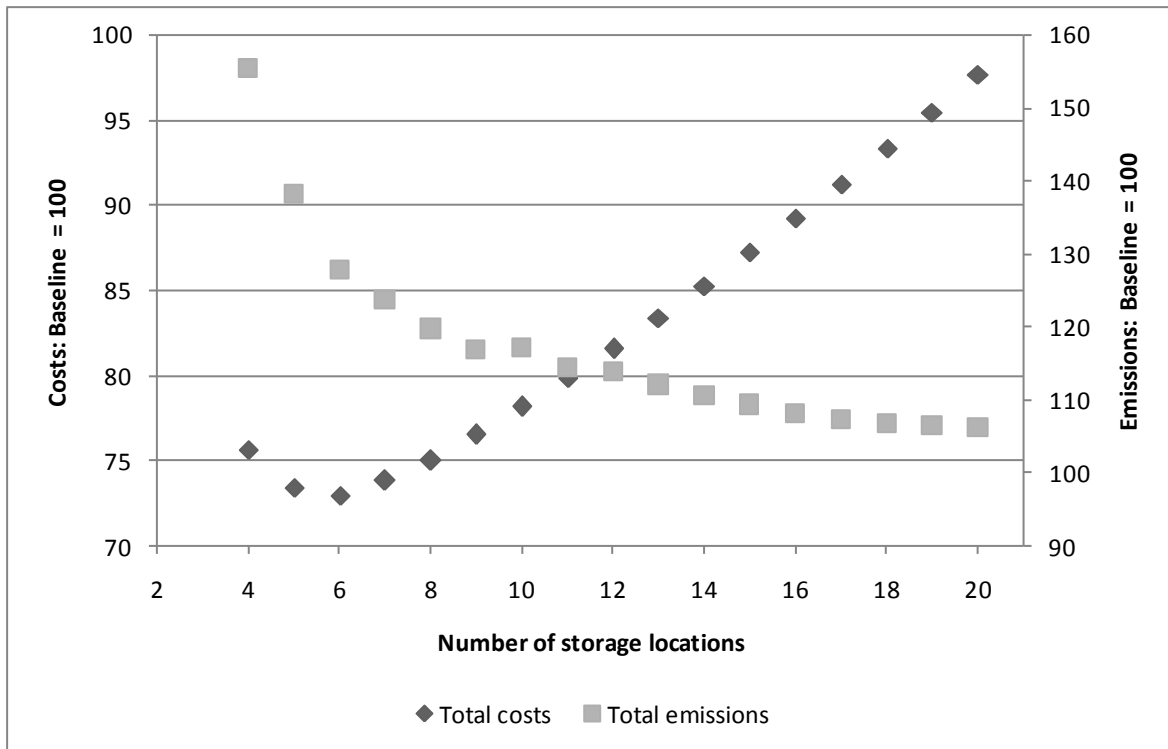
4.5. Impact of carbon costs on the Warehouse Location Problem

Looking only at the economic performance of the results in the p-median and the Warehouse Location Problem, the focal company may favor a distribution network with six operating storage locations. Consequently, the negative impact of this situation on the environment is not considered in the decision-making process. 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 CO2-e emitted through transport activities. 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.

Fig. 6: Efficient frontier of total costs and total emissions
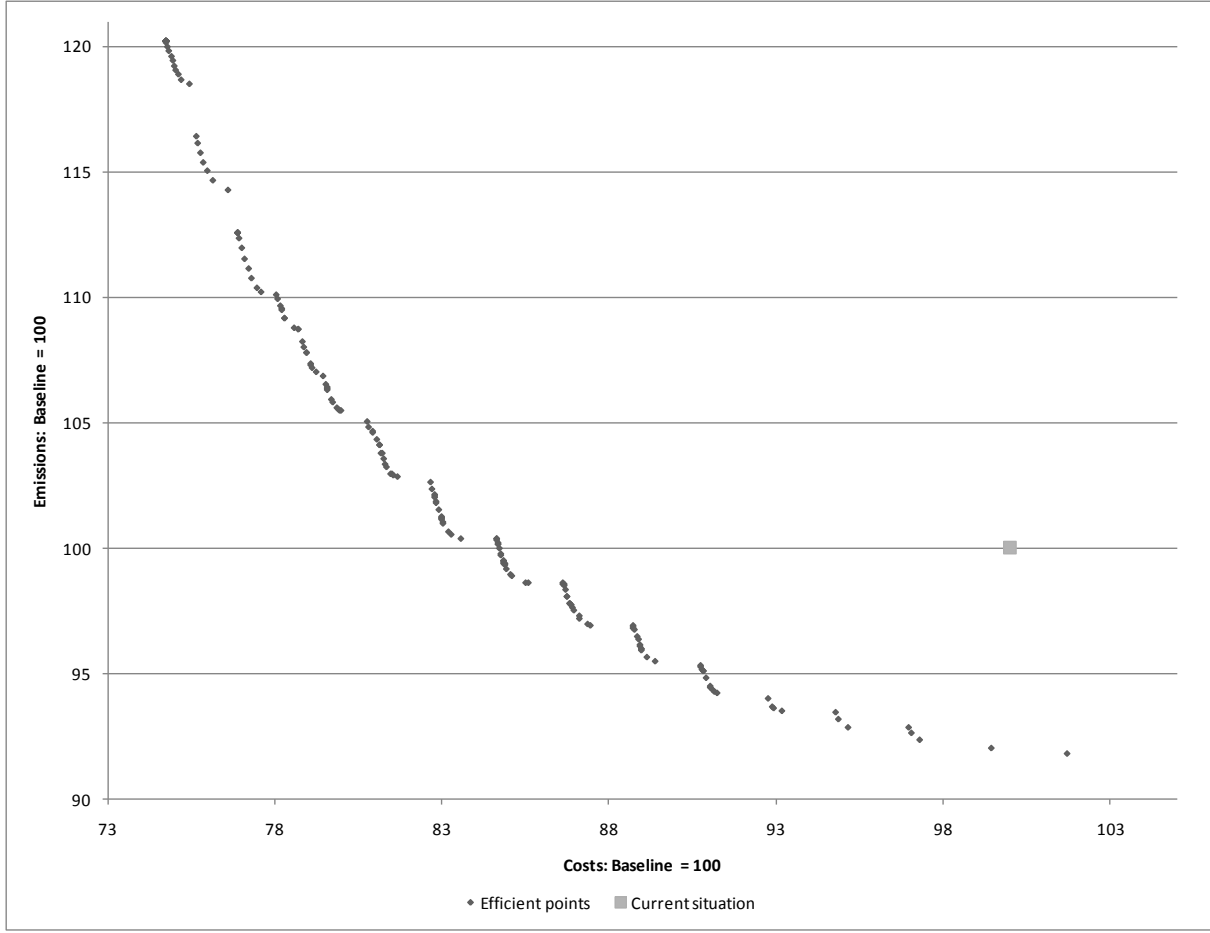
It is interesting to analyze how carbon costs would affect this case study, if they also applied to emissions from transportation. In that case, carbon emissions would have a direct influence on the total distribution costs. Therefore, we assume in our model that for each ton of CO2-e emitted by transportation on rail or road the company is charged a certain amount of money c_e. In this respect, this idea can be interpreted as a tax on carbon emissions that has to be paid per ton of CO2-e emissions from transportation. By applying costs for carbon emissions, total distribution costs in all analyzed network scenarios increase (ceteris paribus). For the Warehouse Location Problem this means extending the objective function to the following expression.

$$min: \sum_{i \in I} c_{0i} x_{0i} + \sum_{i \in I, j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i y_i + \sum_{i \in I, j \in J} v_i x_{ij} + E\, c_e \qquad (8)$$

With this new objective function we want to determine those values of c_e at which the cost-optimal network-design, meaning the number of operating storage locations, changes. Although we found out in the previous analysis that switching from six to seven filling stations increases costs only slightly but reduces emissions, the price for the emission of one ton of CO2-e must exceed 510€ for the cost optimal network to consist of seven instead of six storage locations. This results in 3.3% fewer emissions, but consequently costs are 37.5% higher than in the situation without carbon costs. The cost optimal number of storage locations increases to eight, nine and ten, as soon c_e is greater than 680€, 1100€ and 1380€ respectively. For other values of c_e as the mentioned ones, the network-design is unchanged. The corresponding environmental and economic consequences of a situation like that are

depicted in Table 5 and Figure 7, relative to the cost optimal situation without carbon costs. Depending on the carbon price per ton of CO2-e the total costs are depicted on the primary vertical axis whereas the total emissions are depicted on the secondary vertical axis.

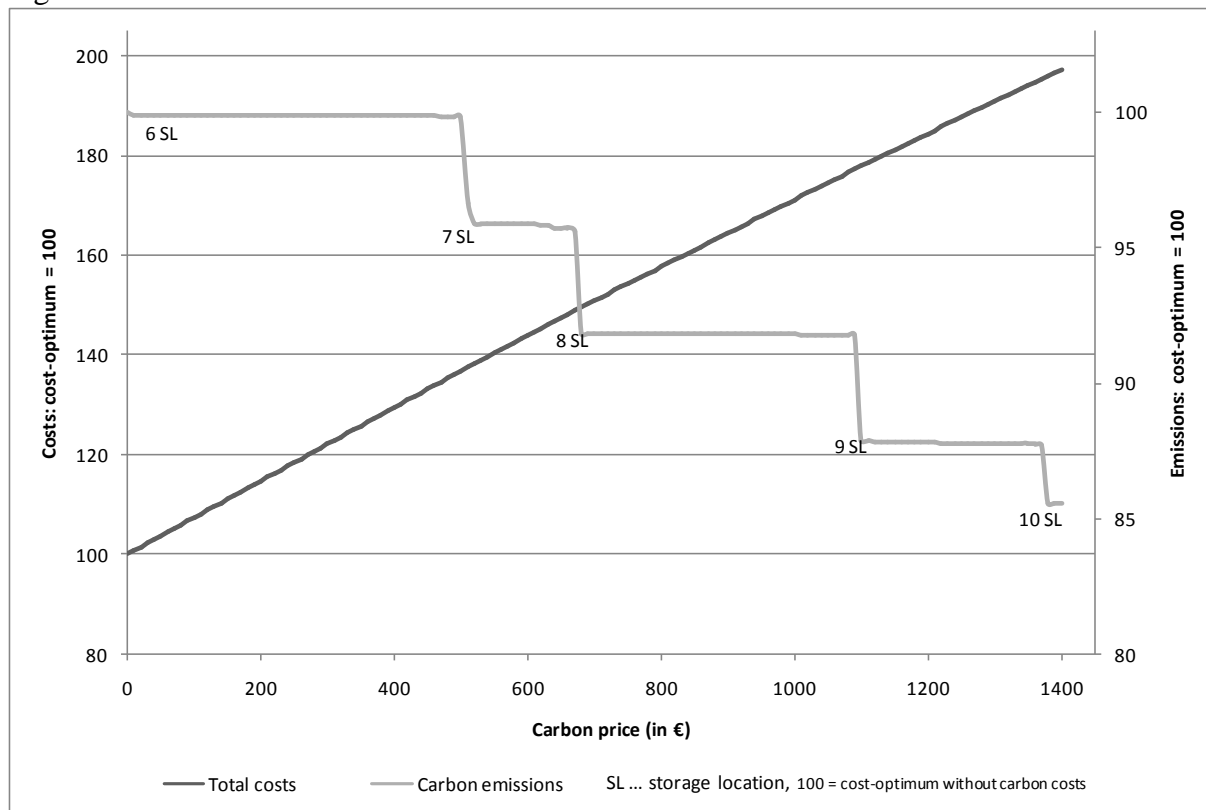Fig. 7: Influence of carbon costs on total costs and emissions

Table 5 clearly shows that with increasing values of c_e the carbon intensive trucks are avoided and secondary transport emissions are reduced. The increases in primary transport activities and primary transport emissions do not compensate the reductions in secondary emissions, thus total emissions are reduced. However, the increasing number of storage locations leads to increases in fixed costs and primary transport costs, since more fuel is transported by rail, but also to a reduction in secondary transport costs. Furthermore, the higher the value of c_e, the higher is the share of carbon costs on the total distribution costs, thereby improving the environmental sustainability but worsening economic sustainability. Currently the costs of buying allowances for emitting one tone of CO2-e under the EU ETS amounts to approximately 7€ (on May 24, 2012). Consequently, this regulatory measure on transport emissions at current prices seems to have no influence on the network-design decision in this particular case study.

Tab. 5: Economic and environmental consequences of carbon costs

c_e in Euro	0€	510€	680€	1100€	1380€
Number of storage locations	**6**	**7**	**8**	**9**	**10**
Operational costs	100	111.0	121.9	132.9	143.8
Primary transport costs	100	101.1	108.9	119.2	123.0
Secondary transport costs	100	95.4	89.1	83.4	79.7
Total distribution costs	**100**	**137.5**	**149.5**	**177.9**	**196.0**
Carbon costs (in % of total costs)	**0**	**36.3**	**46.0**	**71.3**	**87.0**
Primary emissions	100	105.2	112.0	118.7	123.3
Secondary emissions	100	92.2	81.3	71.9	65.9

Total emissions	100	96.7	91.8	87.9	85.6

### 4.6. Comparison of results and implications for the supply chain

Several modeling and solution approaches have been discussed in the course of this work. First, the p-median problem has been modeled and solved using both a heuristic and an exact approach, minimizing secondary transport costs. Second, the Warehouse Location Problem has been solved exactly, optimizing total distribution costs. It turns out that the cost optimal number of operating storage locations (6) is the same in all three situations. However, one storage location and the allocation of demand points to the depots differ to some extent between the optimal solutions of the models, which explains the disparity in the results. Since the Warehouse Location Problem considers total distribution costs, the optimum solution performs slightly better than the results of the p-median problem, but worse in terms of total transport emissions. It is important to notice that in all solutions the operating storage locations are strategically positioned, which keeps the lead times to the filling stations on a manageable level, given that availability of fuel at the depots is granted. Still, compared to the Baseline situation, the average distance to the customers is higher, making a detailed and careful planning of primary and secondary transport processes on a higher level of detail inevitable. It is, hence, to be expected that centralized planning and control of fuel deliveries to the filling stations will become more important in the future. Furthermore, a special focus will have to be put on investigating certain promised service levels to the filling stations as well as to capacity restrictions and future extensions in order to fulfill additional demand with less storage locations also in coming years.

In facility location decisions in general and in this case study in particular, the two objectives of minimizing distribution costs and minimizing transport emissions are clearly in conflict. It is, therefore, usually not possible to optimize both, costs and emissions at the same time. Consider, for instance, the Baseline situation with 20 operating storage locations. Assuming the company currently operates this network with the proposition of cost minimization, the Warehouse Location Problem allocates the demand in a certain cost optimal way. If, however, the company operated the same network on the proposition of emission minimization (changing the objective function of the Warehouse Location Problem to minimize total transport emissions), a different allocation of demand will be the result. This would lead to reductions in emissions compared to the cost optimal Baseline situation of 8.2% but at 1.7% higher costs. In order to show if situations like this can be expected for any given network-design, we compared the results of the Warehouse Location Problem with cost optimization and emission optimization for any given number of operating storage locations.

It can be shown that in any case there is a difference between the cost optimal and the emission optimal situation. On average, optimizing emissions increases total distribution costs by 1.8%, but the environmental impact is reduced by 5.9%. However, if the number of operating warehouses is fixed, there are certain cases when not only the allocation of demand changes but also the warehouses to operate. In particular, if less than seven or more than 14 warehouses should be in operation, the resulting network-design for both objectives is the same, but in any other case, the network-design changes with respect to one or two warehouses. This means that, for instance, given to operate eight warehouses, one warehouse that would be operated in the cost optimal situation would not be in operation in the emission-minimizing situation and contrariwise. Yet, we also wanted to analyze the impact of different demand allocations alone on the environmental performance. Therefore, we fixed the cost optimal network design (in terms of which storages are to operate) and allowed only changes in the allocation, minimizing emissions. In that case, total distribution costs increased on

average by 1.5% but emissions are reduced by 4.9%. This means that altering only the allocation of demand can already lead to reductions in emissions. Furthermore, it shows that although an optimization of both costs and emissions is not possible, the solutions of these two objectives are often quite close to each other. This suggests the proposition that through a small change in a network, like in this case a change of allocation, an improvement of the environmental impact is achieved that is larger than the deterioration of costs. However, this effect is reduced the more centralized a network is organized.

Fig. 8: Comparison of cost minimization and emission minimization
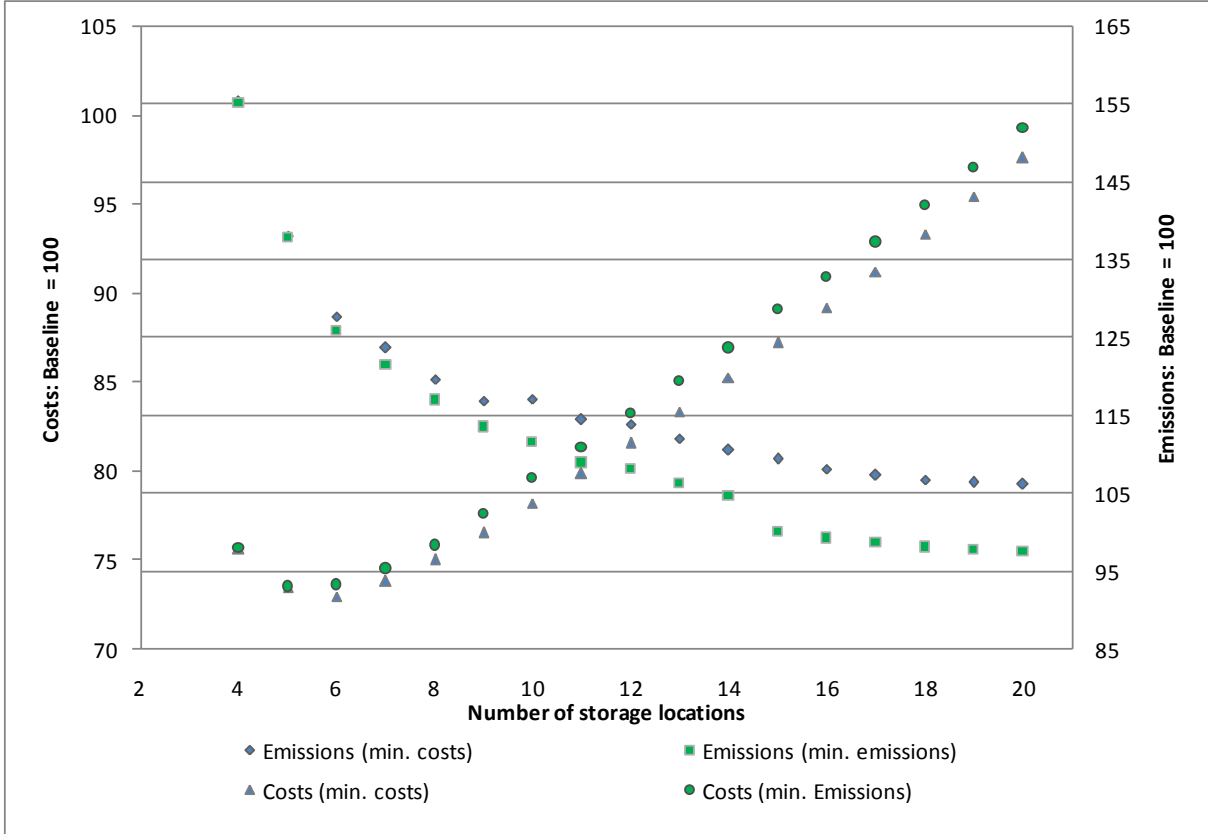
5. Summary and conclusions

On the basis of a real world case study from the petrochemical industry in Europe, this paper shows the effects of changing the distribution network-design on the economic and environmental performance. Two basic models for facility location decisions are considered, namely the p-median problem and the Warehouse Location Problem and are extended to also include environmental criteria in addition to the classical economic ones. Total costs of distribution are taken as an indicator for the economic performance, consisting of primary and secondary transport costs and fixed as well as variable operational costs in the operating storage facilities. As an environmental criterion, carbon emissions from rail and road transportation in terms of CO_2-e are considered. The p-median problem is analyzed using both a heuristic and an exact approach. For the heuristic approach a decision-support tool has been developed in order to integrate expert knowledge and to allow a scenario based analysis. For the exact approach of the p-median problem and the Warehouse Location Problem CPLEX has been used.

The results of these analyses show similar results. Centralizing inventories by reducing the number of operating storage locations leads to decreases in costs until a certain level of

centralization is reached. As soon as the degree of centralization is too high, total distribution costs increase again. Carbon emissions in the network are mainly dependent on the amount of truck transportation in the network, thus the environmental performance worsens with a decreasing number of storage locations. Making use of multi-objective optimization, a clear trade-off between costs and emissions is shown in this case study. It is interesting to see, however, that a small deviation from the cost minimum situation or a different allocation of demand does indeed not increase total distribution costs to a large extent, yet notable reductions in carbon emissions can be achieved by doing so. We also investigated the effects of carbon costs on the optimal number of storage locations and found out that with current prices this kind of regulation does not influence the optimal decision.

Additionally, this paper provides good evidence that simple models in locational analysis can be extended easily to include environmental considerations and allow for a first assessment of economic and environmental sustainability measures. An analysis like that can serve as an adequate basis for further research and for detailed analyses of transport processes in a company's distribution network. Especially when regulations with respect to transport carbon emissions come into force, a detailed analysis of transport processes will be obligatory. This would mean lifting the analysis from a strategic level to a tactical or operational level. In that case, several additional considerations can be incorporated, for example about increasing the efficiency of transportation in the network or the effects of changing the replenishment policy at the filling stations.

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