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Green Facility Location – A Case Study

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ABSTRACT

"Green logistics" is a popular catchword, not only in public and among companies, but also in academia. In this paper we apply the concept of green logistics to the facility location problem: Optimizing the locations of facilities in the general p-median model. This is based on CO2 emissions generated through transportation rather than traditional cost measures, such as physical transportation cost. We examine the results of a real world case study and compare those with each other. Especially implications for real world application are critically discussed.

Keywords

Facility location problem, green logistics, CO2 emissions, p-median problem, decision support systems

INTRODUCTION

Facility location is one of the most important strategic questions to production companies and enterprises offering services to a set of customers. Questions to be answered are often of a two-staged nature: (1) Finding the optimal location for facilities with respect to a certain goal (e.g. cost, service level) among a set of candidate sites. (2) Assigning customers (e.g. consumers, warehouses) to these locations, in cases where more than one facility is being opened.

Traditional models focus on minimizing the cost or the maximum distance to potential facility locations. Without further constraints (for the exact model formulation refer to section 3 Problem Formulation), the former problem is commonly referred to as the p-median problem in literature; the later one is referred to as the p-center problem. The "p" in both models indicates that the number of facilities to be opened is predetermined by the planner. Another class of problem is the 'uncapacitated facility location problem' (UFLP). This type of problem additionally takes in to account fixed location cost and the number of locations to be opened is determined by the model. For these problems exists a vast body of literature with respect to model variations and solution techniques. See Drezner and Hamacher, 2002, and Eiselt and Marianov, 2011 for comprehensive reviews.

The cost is usually measured as distance travelled, travelling time, or monetary transportation cost, weighted by customers' demand. In recent years ecological aspects, such as carbon footprint, and sustainability became more and more important. Those topics moved higher on the agenda of many businesses and their decision makers. This trend is enforced by consumers taking a closer look at the activities of businesses and their contribution to environmental concerns. Consequently decision makers and managers are not only obliged to take the standard Key Performance Indicators (KPI), such as cost or service levels, into their considerations and decision making processes, but also environmental aspects.

In the light of green logistics – a catchword commonly referring to combing logistics and its processes with environmental aspects – a facility location problem (FLP) can also be examined from an environmental standpoint. In this paper we want to determine the effect of taking environmental measures into account for the FLP, instead of traditional ones. The problem constructed will be a classical application: The location of warehouse(s) in a distribution system with physical transport of goods by truck. Our underlying assumption for the following analysis is that the transportation itself accounts for the biggest share of environmental impact/pollution. As a proxy we will focus on CO2 emissions being produced by the combustion of fossil fuels. It makes up more than 80% of manmade greenhouse gas emissions in industrialized countries (U.S. Environmental Protection Agency, 2011, and Olivier, Janssens-Maenhout, Peters and Wilson, 2011) and is assumed to contribute strongly to global warming. Furthermore CO2 is a well known greenhouse gas not only to experts in their field, but also to the general population. Questions to be answered are (1) do CO2 optimal location results differ from classical cost measures and (2) to what extent? Especially the answer – respectively the result – to the last question will be of utmost interest: CO2 emissions and transportation cost are correlated, as both have the distance travelled as an input variable.

We will outline a FLP to determine the new optimal facility location. Competing cost measures for which the model optimizes will be a traditional cost measure – the cost of physical transportation – and CO2 emissions likewise. The target is to create an information system, which enables decision makers to compare results for an optimal location using a traditional cost measure with those using an environmental cost measure. It is crucial to provide a practical model which is a real benefit to managers of a company. Thus not only the optimal location(s) for both measures, but also the trade-off (in money-terms and CO2 emission terms) is of utmost interest. The main findings of this paper are that optimal results for the both cost measures differ, i.e. different facility sites will be established by optimizing CO2 emissions compared to transportation cost. For the examined case study, locations minimizing CO2 emissions can be put up with only a slight increase in physical transportation cost.

This paper is structured as follows: In section 2 we start with formulating the requirements to the decision support systems and the model. We then present in section 3 the mathematical formulation of the problem. Consecutive in section 4 we will make the link to a real world example and present results respectively. We will conclude with the findings in section 5 and discuss its implications for real world applications.

REQUIREMENTS ANALYSIS

Finding the optimal warehouse location is a problem that occurs in all stages of the supply chain planning process. It is an important aspect in the design of a new supply chain from scratch, for example when a company is entering a new market and needs to establish warehouse structures to ensure a smooth distribution. It is just as important for reevaluating existing ones: Existing warehouses reach their capacity limits and cannot be extended, or a company acquires a competitor and all of a sudden parallel structures exist that need to be consolidated. Mathematical models can help to support supply chain planners in order to find optimal warehouse locations. As discussed in the introduction, environmental aspects become more and more important in supply chain design. Especially CO2 emissions and efforts to reduce them are on the agenda of many businesses. Additionally customers are becoming more sensitive towards environmental activities of companies and monitor their efforts closely. A carefully designed supply chain, which is accounting for environmental aspects, may give businesses a competitive advantage as it can be publicly promoted as such.

Following the introduction we will now formulate the requirements identified for the location model and decision support system which will be developed in this study. A description of each is given thereafter.

Requirement 1: Minimize transportation CO2 emissions (carbon footprint)

Requirement 2: Comparison of CO2-footprint optimal location(s) with traditional transportation cost optimal location(s)

Requirement 3: Allow for green-field planning: candidate sites spread equally over customer area

Requirement 1 will be directly implemented in the formulation of the facility location model. The model should minimize the transportation carbon footprint associated with the facilities to be located. Instead of a traditional cost measure, CO2 emissions are used as a cost in the models' objective function. Requirement 2 directly relates to requirement 1 stated above: A decision maker usually wants to know how far a CO2-emission-optimal solution is away from a cost-optimal solution in monetary terms. If the trade-off is known to the decision maker, the selection of a CO2-emission-optimal solution over a cost-optimal will be based on his/her utility function. Requirement 3 has been derived from the design of the model as a part of a decision support system. By ensuring that potential facility sites are spread equally over the considered area, it allows the decision maker to vary his/her input parameters and conduct "what-if" analyses. The system can thus be used for differing applications and variations of input parameters (such as regional demand shifts). It additionally contributes to the fact that the decision maker does not want to limit the candidate sites to a specific geographic region within the customer area or to have too long distance between potential sites. This is especially important if more than one facility is to be located.

We now want to give a brief overview of facility location in literature: The first one known to state the problem was Fermat (1601-1665) (Drezner, Klamroth, Schöbel and Wesolowsky, 2002). Almost three centuries later the German economist Alfred Weber discusses the problem in an industrial context: a central facility needs to be located among a set of demand points – each with a weight associated depicting the quantity shipped – in such a way that the weighted sum of distances from the demand points to the central facility is minimized. In the appendix of his book "Theory of the location of industries", Georg Pick gives the first mathematical formulation of the problem (Weber, 1909). Starting in the 1960s, the problem received greater attention in the academic world, which still persists today. The facility location problem – with all its variations – is a well studied field in the operations research literature. The work consists of either new problem formulations and/or procedures to solve those. Two new streams received greater attention in recent years, which are facility location under uncertainty and formulations incorporating multiple objectives. See Arabani and Farahani 2011; Farahani, SteadieSeifi and Asgari, 2010; Melo, Nickel and Saldanha-da-Gama, 2009; Sahin and Süral 2007; Snyder 2006; Hamacher and Nickel 1998 for reviews and surveys on facility location models. Lately environmental aspects and measures are accounted for in facility location models. That is the field to which this work contributes to. The work on facility location with an environmental objective function is limited in academia. Table 1 gives an overview of recent papers concerning environmental aspects in the context of facility location and/or supply chain design (not limited to FLPs). Furthermore those papers are evaluated with respect to the requirements listed above. None of the papers directly compares financial/transportation optimal solutions with CO2/environmental optimal solutions, but rather tries to balance both in the objective function.

Article	**R1**	**R2**	**R3**	**Remarks**
Hugo and Pistikopoulos, 2005	(X)	-	-	Mixed integer linear programming model for the design and long-range capacity planning of a bulk chemicals supply chain; life cycle analysis model using Eco-Indicator 99 method as environmental measure Objective function: net present value and environmental impact optimized simultaneously
Quariguasi Frota Neto, Bloemhof-Ruwaard, van Nunen and van Heck, 2008	(X)	-	-	Multi-objective programming, development of framework for the design and evaluation of sustainable logistic networks, environmental impact measured by global warming potential, acidification, and others Objective function: profitability and environmental impacts balanced
Harris, Mumford and Naim, 2009	X	(X)	-	UFLP Objective function: cost, environmental impact and uncovered demand optimized simultaneously
Harris, Mumford and Naim, 2011	X	(X)	-	Capacitated facility location problem Objective function: financial cost and CO2 emissions optimized simultaneously Focus on solution with evolutionary algorithm
Pinto-Varela, Barbosa-Póvoa and Novais, 2011	(X)	-	-	Planning and design of supply chain structures for annual profit maximization while considering environmental aspects (Eco-indicator methodology), flow optimization, facilities fixed Objective function: Profit and environmental impacts balanced using an optimization approach adapted from symmetric fuzzy linear programming
Ubeda, Arcelus and Faulin, 2011	(X)	-	-	Optimization of transport planning and vehicle routing under environmental aspects, case study Objective function: Travel distance minimization in vehicle routing
Legend: R1…R3: Requirement 1 to requirement 3, “X”: fulfilled, “(X)”: partially fulfilled, “-“ not fulfilled				

Table 1 - Related worked assessed by fulfillment of requirements

PROBLEM FORMULATION

The problem can be formulated as the standard p-median problem, which can be found in the literature (Hakimi, 1964, 1965). The following notation is being used:

I = the set of demand nodes, indexed by i
J = the set of potential facility sites, indexed by j
h_i = demand at node i
c_{ij} = cost incurred between node i and potential site j
p = number of facilities to be located

The decision variables of the problem are:

$$y_{ij} = \begin{cases} 1 \text{ if demand node } i \text{ is assigned to a facility at node } j \\ 0 \text{ if not} \end{cases}$$

$$x_j = \begin{cases} 1 \text{ if facility } j \text{ is chosen} \\ 0 \text{ if not} \end{cases}$$

The problem can now be formulated as follows:

Minimize $$\sum_{i \in I} \sum_{j \in J} h_i c_{ij} y_{ij} \quad (1)$$

subject to:

$$\sum_{j \in J} x_j = p \quad (2)$$

$$\sum_{j \in J} y_{ij} = 1 \qquad \forall i \in I \quad (3)$$

$$y_{ij} - x_j \le 0 \qquad \forall i \in I, j \in J \quad (4)$$

$$x_j \in \{0,1\} \qquad \forall j \in J \quad (5)$$

$$y_{ij} \in \{0,1\} \qquad \forall i \in I, j \in J \quad (6)$$

The objective function (1) minimizes the demand-weighted total cost incurred. Cost hereby refers to (a) actual logistics cost, based on distance zone, weight and freight rate, or (b) CO2 emissions. Constraint (2) ensures that exact p facilities are being opened. Constraint set (3) ensures that each demand node is assigned to exactly one facility. Constraint set (4) guarantees assignment of demand nodes only to open facilities. Constraint sets (5) and (6) restrict the decision variables of opening facilities and assigning demand to facilities to be binary. Note that in the case of assigning only one facility, the problem can be reduced to

Minimize $$\sum_{i \in I} h_i c_{ij} \qquad \forall j \in J$$

The number of facilities to be selected is predetermined and not a decision variable of the model. Consequently fixed cost associated with the construction and operation of the facilities need not be incorporated into the model formulation. Moreover this cost does not influence the selection of candidate sites for fixed values of p sites to be chosen. The problem can be solved in polynomial time for a fixed number of facilities to be located. It gets NP-hard if the number of facilities is a decision variable of the formulation, which is not the case in the problem formulation (Current, Daskin and Schilling, 2002).

We now present a numerical example to the optimization problem stated above with $p=1$. We assume to have four candidate sites and four demand nodes. Table 2 gives an overview of the distance and demand information, and Table 3 an overview of freight rates depending on distance zone and weight. In the case of $p=1$, all demand nodes are assigned to one facility site. For the cases $p>1$, the demand nodes are assigned to its closest facility site.

	Distance from facility candidate sites j (in km)				Demand data	
Demand i	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**No. of deliveries**	**Avg. weight/delivery**
1	248	166	98	88	79	27 kg
2	250	168	108	92	154	132 kg
3	256	174	114	141	194	142 kg
4	253	171	111	98	139	34 kg

Table 2 - Distances and demand data of numerical example

Values in EUR/100kg	Distance zones (km)			
	Zone1	**Zone2**	**Zone3**	**Zone4**
Weight (kg)	**0-50**	**51-100**	**100-200**	**>200**
0-31.4	17	19	23	25
31.5-50	16	18	21	23
51-100	15	17	20	22
101-150	14	16	19	21

Table 3 - Freight rate sheet numerical example

The optimization problem is then solved by calculating the total CO2 emissions, respectively physical transportation cost, for the potential facility sites. In the numerical example, Table 4 and Table 5 show the fully enumerated results. Facility site three is the optimal facility with respect to CO2 emissions, while facility site four is the optimal one with respect to transportation cost.

Values in kg CO2	CO2 emissions from facility candidate sites j			
Demand i	**Site 1**	**Site 2**	**Site 3**	**Site 4**
1	11,422	7,645	4,514	4,053
2	22,446	15,083	9,696	8,260
3	28,954	19,680	12,894	15,947
4	20,502	13,857	8,995	7,942
Total emissions	**83,324**	**56,266**	**36,099**	**36,202**

Table 4 - CO2 emissions numerical example

Values in EUR	Transportation cost from facility candidate sites j			
Demand i	**Site 1**	**Site 2**	**Site 3**	**Site 4**
1	533	491	405	405
2	4,269	3,862	3,862	3,252
3	5,785	5,234	5,234	5,234
4	1,087	992	992	851
Total cost	**11,674**	**10,579**	**10,494**	**9,743**

Table 5 - Transportation cost numerical example

CASE STUDY

We are now going to present a real world company example of a facility location problem. The problem will be constructed using input data of the company – in the following referred to as Greenfinch Ltd. – and the CO2 optimal results will be compared to the transportation cost optimal results for a number of up to five facilities to be located ($p=1...5$). Let us give a brief introduction to Greenfinch Ltd.: It is active in the consumer goods industry. The value chain reaches from own manufacturing to distribution to customers (wholesalers and installers), both on an international level. Warehouses are operated on the echelon between production sites and customer locations. Greenfinch Ltd. has grown significantly over the last years – organically and through acquisitions. This led to duplicate structures, especially on the warehousing level. Additional triggers to review and optimize the current warehouse setup are long grown established structures. Germany – one of the core markets with high strategic importance – serves as an example for the following illustration of the problem: Currently two central warehouses exist. This structure has shown to be inefficient and management is induced to identify a new warehouse location setup. A single central warehouse has shown to be the most efficient structure to serve the German market (reasons include minimization of administrative effort and stock levels at this warehousing stage and will not be discussed in further detail in this study). Customers are spread over all parts of Germany.

Methodology

Coming from the situation described above, the decision maker wants to input available company data into the model and get information on the optimal warehouse location based on the defined objective function. In this study it is defined as (a) carbon footprint minimization and will be compared to (b) logistics cost minimization. Especially the information about the tradeoff between a CO2 emission optimal and a cost optimal solution is of particular interest. How much additional logistics cost does Greenfinch Ltd. incur in order to minimize its carbon footprint? Although management has decided to consolidate two warehouses into one, the optimization will be carried out for up to five facilities to be located (scenario $p=1$ up to $p=5$). The reasoning is to extend the research aspect of this paper and to provide a sensitivity analysis to the decision maker. Warehouse construction costs are assumed to be equal in Germany, independent of the geographic region it is located in. Operating costs are assumed to be a linear function of demand assigned to the warehouse. Both cost components are thus not a part of the mathematical formulation and optimization, but are rather evaluated separately.

The implementation will be realized with GAMS using the CPLEX solver. The available company data will be prepared so it can be processed by the optimization software. In a second step each of the five scenarios ($p=1…5$) for the CO2 emission optimization and for the physical transportation cost optimization will be carried out, resulting in ten runs in total. Simultaneously, the solution space will be explored to find the Top5 'second best' solutions. In a last step the results will be compared with regard to CO2 emissions and physical transportation cost for each of the scenarios.

Data set

The analysis is based on available company data: customer demand (yearly delivery frequency as a proxy), weight of transported goods and freight rates from the actual contracted logistics provider. Publicly accessible information on distances between customers and potential facility sites makes up the distance matrix used for the analysis. Candidate sites were derived from placing a grid over Germany, leading to 191 potential facility locations. As explained above, the grid was used in order to cover the customer space equally. CO2 emissions are based on the CO2 produced by combustion of 1l Diesel, which is the primary source of fuel used for trucks in Germany. Combined with the average fuel consumption per kilometer travelled, this leads to the CO2 emissions in kilogram (kg) per kilometer (km) used in the analysis. Basis for the calculation is a 7.5 ton truck with an average fuel consumption of 22l/100km. The combustion of one liter diesel generates 2.65 kg CO2 per liter, which leads to 0.583 kg CO2/ km. Please refer to Appendix 1 for an overview of the input data used.

Simulations results and managerial implications

The problem formulation was implemented as a GAMS model. Optimization was carried out for $p=1$ up to $p=5$ facilities to be located, using the CPLEX MIP solver. The system used was running with an Intel®Core™2 Duo CPU 2.26GHZ processor and 1.94GB RAM. Computation time for the results is shown in Table 6.

# of facilities (*p*)	CPLEX Cost (sec.)	CPLEX CO2 (sec.)
1	0.02	0.02
2	14.11	36.42
3	10.83	50.58
4	9.53	28.39
5	3.89	22.72

Table 6 - CPLEX optimization runtime

Table 7 and Table 8 are showing the optimal results for CO2 emissions and transportation cost respectively. More importantly both also point out the additional cost of a CO2 emission optimal over a transportation cost optimal solution and vice versa. The case study shows that cost potential abandoned by choosing the CO2 optimal solution is in the range of 0.4-3.9%. For locating up to 4 facilities it is even smaller than 1.9% for all of the four cases. The optimization with the traditional cost measure – transportation cost – shows that the discarded CO2 emission reduction potential is in the range of 3.1-9.0% for the studied cases $p=1...5$.

# of facilities (*p*)	CO2 emission optimal solution	Cost increase to cost optimal solution	
	Objective value (Mio. kg CO2)	in percent	absolute in TEUR
1	10.9	1.0%	0.02
2	7.7	0.4%	0.01
3	6.1	1.4%	0.02
4	5.0	1.9%	0.03
5	4.5	3.9%	0.06

Table 7 - CO2 optimization results for *p=1...5*

# of facilities (*p*)	Freight cost optimal solution	CO2 emission increase to CO2 emission optimal solution	
	Objective value (Mio. EUR)	in percent	absolute in Mio. kg CO2
1	1.98	9.0%	0.98
2	1.77	4.7%	0.29
3	1.64	6.9%	0.36
4	1.55	3.1%	0.16
5	1.49	4.2%	0.19

Table 8 - Transportation cost optimization results for *p=1...5*

The solution space was explored, in addition to the optimal results, to find solutions within a range of 2.5% of the objective value for the CO2 case and 0.5% of the objective value for the transportation cost case. The top five solutions for both optimization runs and for the five scenarios (*p=1...5*) were selected. The main reason for doing these additional analyses was to provide sensitivities and a view on the trade-off to decision makers. Figure 1 and Figure 2 show the results for *p=3* and *p=4* respectively. The remainder is illustrated in Appendix 2. Bold markers denote the optimal solution. In a business environment a decision maker most likely has to balance the minimization of CO2 output with an adequate cost position. As can be seen in the cases *p=3* or *p=4*, s/he can choose from intermediate solutions, which offer both: cost reduction compared to the CO2-emission optimal solution and CO2-emission reduction compared to the transportation cost optimal solution.

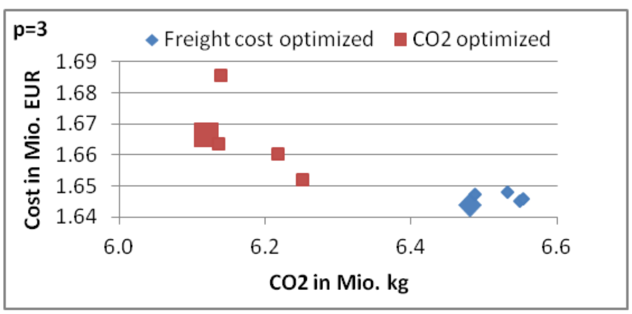

Figure 1 - Comparison Top5 solutions for *p=3*

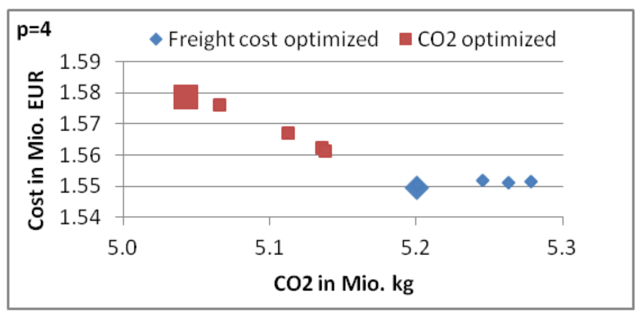

Figure 2 - Comparison Top5 solutions for *p=4*

Discussion

Above results indicate that a CO2 emission optimal solution differs from a transportation cost optimal solution. For Greenfinch Ltd. and its decisions makers it is important to compare those results to the status quo, i.e. two facility locations. As explained above, the goal is to consolidate both warehouses into a single one. For comparison purposes, the emissions and cost of the actual warehouse setup was calculated based on the model parameters. Greenfinch Ltd. incurs a total of 2.2 Mio. EUR in transportation cost and 16 Mio. tons of CO2 emissions. Establishing one consolidated warehouse would thus save a total of 32% (26%) in CO2 emissions and 10% (11%) in transportation cost for the CO2 (transportation cost) optimal solution. As the difference in cost amounts to only one percentage-point, Greenfinch Ltd. can follow the recommendation of establishing its warehouse at the CO2 emission optimal facility location. The slight plus in cost can be seen as an investment into marketing and the environmental friendly supply chain design promoted as such to customers (CO2 emission reduction by one third).

Implementation as a decision support system

Besides the pure mathematical implementation using GAMS/CPLEX, the question to answer for Greenfinch Ltd. – where is the optimal location for one warehouse to be located – was implemented as a decision support system. It provides a user-friendly interface and data/result presentation, compared to the optimization software GAMS. The system consists of two modules: Data input and results. The first one allows the decision maker to input company data, such as demand by region and freight rates, and the second one presents and visualizes the results. With the data input module the decision maker is able to conduct scenario and sensitivity analysis by varying his/her input data, e.g. to anticipate future demand growth or changes in freight rates. The result module displays the optimal warehouse location for both CO2 and transportation cost optimization on a map. As carried out in the analysis above, the solutions ranked two to five are additionally displayed on the map. The visualized results are accompanied by tables, which show the top five solutions and trade-offs respectively.

CONCLUSION

This paper presents the application of green logistics to the facility location problem, more specifically the p-median problem. CO2 emissions were identified as a proxy for environmental impact on a distribution network. The analysis conducted in the case study compared CO2 emissions and physical transportation cost. Both served as competing cost measures for the optimization of the facility location problem. The optimization was carried out for up to 5 facilities to be located. Results show that for each scenario (i.e. number of sites to be located) the solutions which fulfill the optimality conditions of CO2 emission based and transport cost based optimization are different. The cost increase for CO2 optimal compared to transport cost optimal locations is within a range of 0.4-3.9% for the cases examined. The increase in CO2 output of the cost optimal compared to the CO2 emissions optimal solutions is within a range of 3.1-9.0%.

From the perspective of companies that actively want to reduce their CO2 emissions, this relatively small, model-based cost increase opposed to a transportation cost optimal solution is almost negligible for two reasons: First of all there is a variance from modeling/planning to real world results, as other variables not accounted for in the model influence cost by a great deal (e.g. fuel cost, demand shifts, etc.). Secondly this small cost increase can be seen as an investment into marketing: Companies can actively promote to customers that their supply chain design took environmental aspects into account and minimizes CO2 emissions. At the same time they do not risk an ‘explosion’ of transportation cost compared to the optimal solution using the physical transportation cost as an optimization measure.

Nevertheless, for most companies cost will always play an important role in investment decisions and it is less likely that supply chain decisions will be purely based on environmental aspects. As facility location is always a decisions that is long-term oriented, we believe that there exist more effective, short- to mid-term measures a company can introduce to lower its environmental impact. Examples include fleet optimization (vehicles with lower emission standard, hybrid or electric vehicles), route optimization, and consolidation or utilization optimization, just to name a few.

Another aspect that should be mentioned is that optimizing for CO2 emissions does not reinvent the wheel, but is more or less a “greener” branding of what already exists: Both CO2 emissions and physical transportation cost are a function of distance (and weight). Thus, for traditional ways of transport results will differ, but presumably not a great extent, as this case study indicates. Also, for extensions to the model including fixed cost (e.g. CO2 emissions of facilities opposed to operating cost), both will be based on similar input factors (size of the facility, utilization, handling).

Yet, green logistics in facility location offers interesting investigative opportunities. The scope should be extended from purely focusing on CO2 emissions from transport and facility operation to a more general view on environmental impact of facility locations. A field of research which might offer greater opportunities is a holistic view on environmental impact caused by facility location, e.g. including economic indicators. Those do not only take into account environmental pollution, but also other factors influencing the environment. An example is the Eco Indicator 99, which includes damage to human health, ecosystem quality and resources (Hugo and Pistikopoulos, 2005).

APPENDIX 1 – INPUT DATA ILLUSTRATION

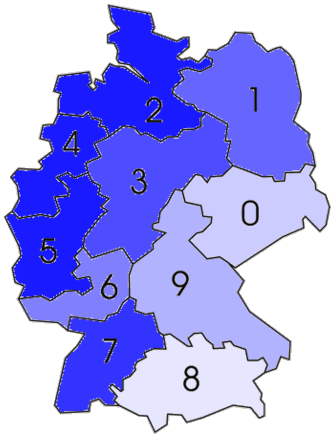

Figure 3 - Demand distribution on post code level (aggregated)

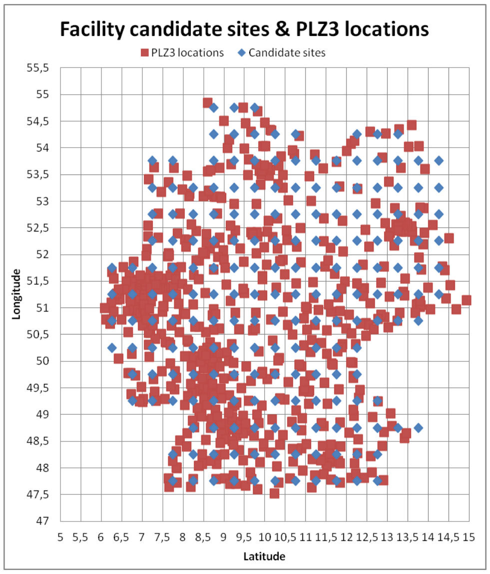

Figure 4 - Spatial distribution of facility candidate sites (grid) and demand

Values in km		**Facility candidate sites j**			
Demand i	**PLZ3**	**Site 1**	**Site 2**	**Site …**	**Site 191**
1	**010xx**	640	622	…	53
2	**011xx**	636	619	…	56
3	**012xx**	648	630	…	61
…	**…**	…	…	…	…
661	**999xx**	398	380	…	325

Table 9 - Distance matrix from demand point *i* to candidate site *j*

Values in EUR/100kg	**Distance zones (km)**			
	Zone1	**Zone2**	**Zone …**	**Zone n**
Weight (kg)	**0-50 km**	**51-100 km**	**…**	**>701 km**
0-31.4	17	18	…	31
31.5-50	16	17	…	30
51-100	15	16	…	29
…	…	…	…	…
>25,001	1	2	…	10

Table 10 - Exemplary freight rates from logistics provider contract

APPENDIX 2 – TOP5 SOLUTIONS FOR P=1, P=2, P=5

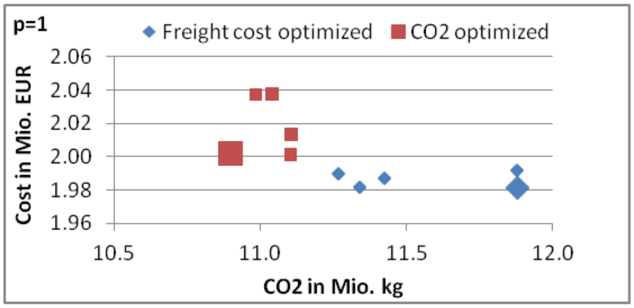

Figure 5 - Comparison Top5 solutions for *p=1*

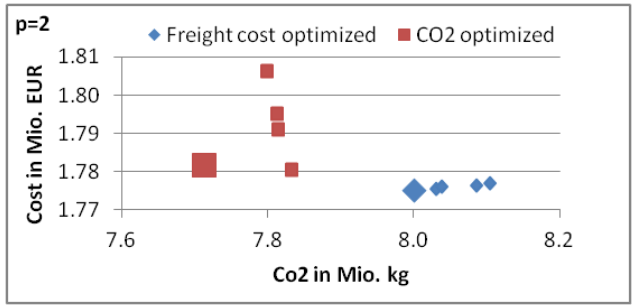

Figure 6 - Comparison Top5 solutions for *p=2*

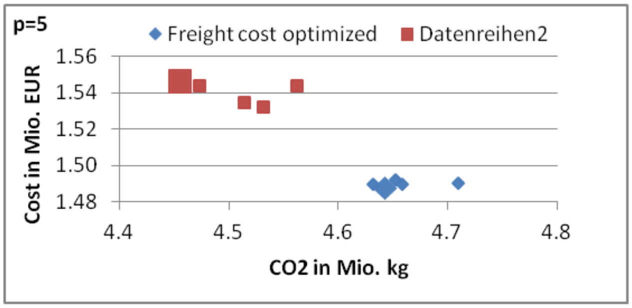

Figure 7 - Comparison Top5 solutions for *p=5*

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