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Redesigning supply chains – An industrial case study

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Abstract

In these turbulent times, companies are forced to rethink their operations every now and again. Naturally, their supply chains represent one of the main focuses of this process. The results of an industrial project on the analysis and potential restructuring of the European distribution network of a global manufacturing company are presented in the paper. In addition to providing the cost-optimal solution, it is demonstrated how the optimal network structure depends on the parameters of the considered cost factors. The consequences of the possible restructuring of the network on the transportation-related CO_2 emission are also treated.

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1. Introduction

There are numerous reasons that compel companies to call into question the adequacy of their current and planned operations. Running their supply chains is no exception.

Among others, natural catastrophes, political uncertainties, pandemics, significant changes in the economic environment, the emergence of new business models, the growing importance of environmental sustainability and the need for circular economy can be mentioned in this respect.

These challenges have to be considered in both the design and the redesign phases of supply chains.

Focusing on this topic, related approaches – some of them developed by the author – are outlined in Section 2.

An industrial problem, namely how to make a global manufacturing company's worldwide supply chain more efficient, however, not neglecting the environmental sustainability aspects either, is introduced in Section 3, together with the approach proposed.

The achieved results are summarized in Section 4, including the cost-optimized structure of the European distribution network as part of the supply chain dealt with, and its dependence on the parameters of the cost factors taken into account. It is also determined what the transportation-related CO_2 emission amounts to in the different cases.

Finally, the conclusions are drawn in Section 5.

2. Supply chains' (re)design

As a reaction to one – or many times simultaneously to a subset – of the challenges enumerated in Section 1, the (re)design of supply chains gained special emphasis, which fact is manifested in the literature.

The randomized local rewiring (RLR) approach is presented in [1] for robustness evaluation of original and modified (rewired) distribution networks. It is pointed out that the robustness of the investigated distribution networks can be significantly affected by proper modifications in their topologies.

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In [2,3], a methodology and a framework are introduced, integrating graph theoretical methods, digital simulation and optimization for the holistic, quantitative analysis of supply chains' structural and operational robustness and complexity, as well as efficiency, and for the support of their (re)design and management. It is shown that with appropriate changes in both the structural and the operational complexity, the robustness can be significantly enhanced, while sometimes maintaining – rarely even increasing – the level of profitability [3].

Expectedly, as a response to the COVID-19 pandemic, existing supply chains will be redesigned, e.g. the length of them will be shortened, their width increased, multiple sourcing will be more frequent [4] and intertwined supply networks will be formed [5].

In the review paper [6], 24 challenges that may hamper the process of redesigning supply chains for circular economy are identified and systematized. Supply chains' redesign using blockchain technology, circular economy principles and COVID-19 experiences is treated in [7]. Manufacturing platforms, in many respects, change completely the ecosystem in comparison with the situation in classical supply chains [8].

A mixed integer programming mathematical model for determining the locations of distribution centers (DCs) in green supply chains is given in [9]. The impacts of the crude oil price on the transportation mode options and on the DC locations are also investigated.

In [10], cooperative game theory is used for allocation of transportation cost and CO_2 emission in pooled supply chains given by the horizontal cooperation among several independent supply chains in a retail logistics network in France. A reduction of 25.98% in the transportation cost (including the carbon tax) is reported on.

The combination of a genetic algorithm and a convex optimization method is proposed for joint optimization of logistics infrastructure investments and subsidies in a regional logistics network in China, with CO_2 emission reduction targets [11].

An approach to achieve trade-offs between the economic and the environmental aspects of supply chains' sustainability is introduced in [12]. It consists of the following steps:

1. *Estimation of the demand and its geographical distribution* for the product(s) within the area to be served by the supply chain.
2. *Determination of the locations* (if they are not known) *of the potential DCs* (greenfield analysis (GFA)) by the center of gravity (CoG) method.
3. *Profit-oriented optimization of the whole supply chain structure*, in the general case by mixed integer linear programming (MILP), and in the case of discrete manufacturing by integer linear programming (ILP).
4. *Generation of alternative supply chain structures for trade-offs between the economic* (e.g. profit) *and the environmental* (e.g. CO_2 emission) *aspects* by constrained optimization.
5. *Characterization of the different cases from the viewpoints of structural robustness and complexity* by using graph theory based methods.

On a multi-level supply chain, it is illustrated that with relatively minor relaxations of the expected profit, such supply chain structures can be formed, which not only secure the reduction of the transportation-related CO_2 emission, but also possess increased structural robustness and complexity [12].

3. The industrial problem and the approach used

A project with a global manufacturing company provided an opportunity to investigate the applicability of some of the results introduced in [12] in an industrial setting. The company owning a worldwide supply chain had the intention to test whether it could be made more efficient, however, taking the environmental sustainability aspects also into consideration.

The focus of the investigations was put on the logistics realized from the company's European logistics center (LC) located in Maarssen, the Netherlands. The following main questions were raised partly at the beginning of the project and partly during its accomplishment:

- Is it appropriate to have only one LC in Europe, and what LC location(s) would be optimal considering the demand with its geographical distribution, and the different cost factors which have influence on the European operation of the company?
- How does the optimal structure of the distribution network depend on the parameters of the cost factors considered?
- What are the consequences of the possible restructuring of the network on the environmental load caused by the transportation?

The main steps of the approach set up were as follows:

1. *Interpretation and analysis of the data* given by the company.
2. *Determination of the potential LCs' locations* (GFA) by the CoG method.
3. *Cost-oriented optimization of the distribution network* by ILP.
4. *Generation of different network structures through cost minimization under various parameters, and their comparisons* concerning:
   - number and locations of LCs,
   - different kinds of costs, and
   - transportation-related CO_2 emission.

Please note that the first three steps above are practically the same as in the approach described in [12] (and at the end of the previous section).

In the project, the results achieved by using the approach were compared with the baseline situation.

3.1. Specifics of the problem

By filtering and analyzing the 1-year data available for the 117,358 shipments realized from the LC, it could be determined that 93.19% of the products (6,883,214 from 7,385,879) were transported by trucks. 19 destination countries were concerned in these shipments.

The demands which were served by trucks were also determined for each of these countries. Germany was found to be the largest market in this sense, with a demand of 2,608,536 products which took 37.9% of the products delivered by trucks from the Maarssen LC.

Mainly because the related database contained the addresses in different ways, sometimes even misspelled, the exact delivery points of the orders within the countries were hard to determine reliably.

The products were computer components and belonged to the same product family. They had various capacities, but similar geometrical dimensions and weights.

Taking the above circumstances into consideration, the following specifications and assumptions were derived:

- Investigations were made on historical data of a 1-year period, related to the deliveries from Maarssen.
- Only truck transportation was considered.
- Countries' yearly demands were aggregated in the capitals.
- Products were considered to be equal.
- 100% service level was aimed to reach.

Consequently, for Steps 3 and 4 of the approach described above, the following ILP model can be formulated:

Indices

i	LC
j	Capital

Input parameters

I	Number of potential LCs
J	Number of capitals
d_fcost_i	Daily facility cost of LC *i*
$dist_{i,j}$	Distance between LC *i* and capital *j*
dem_j	Demand for the product in capital *j*
$gvol$	Geometrical volume of a product
$ctruck$	Capacity of a truck
km_tcost	Kilometric transportation cost of a truck
km_CO_2	Kilometric CO_2 emission of a truck
$tper$	Investigated time period
M	A large number (in the present case at least the total demand)

Decision variables

$x_{i,j}$	Number of products transported from LC *i* to capital *j*
y_i	1 if LC *i* is used, 0 otherwise

Minimize

$$t_cost = t_fcost + t_tcost \quad (1)$$

where

$$t_fcost = tper * \sum_{i=1}^{I} y_i * d_fcost_i \quad (2)$$

and

$$t_tcost = km_tcost * t_dist \quad (3)$$

with

$$t_dist = \sum_{i=1}^{I}\sum_{j=1}^{J} x_{i,j} * \frac{gvol}{ctruck} * dist_{i,j} \quad (4)$$

Subject to

$$\sum_{i=1}^{I} x_{i,j} = dem_j \quad \forall j \quad (5)$$

$$M * y_i \geq \sum_{j=1}^{J} x_{i,j} \quad \forall i \quad (6)$$

$$x_{i,j} \in N \quad \forall i,j \quad (7)$$

$$y_i \in \{0,1\} \quad \forall i \quad (8)$$

Equations (1)-(4) define the total cost, the total facility cost, the total transportation cost and the total distance covered by trucks, respectively. The demand constraints are given in (5). The linking constraints in (6) ensure that no shipments are initiated from an LC that is not used. The constraints on the *x*'s and the *y*'s, namely that they must be natural and binary numbers, respectively, are denoted in (7) and (8).

The total transportation-related CO_2 emission can be computed as

$$t_CO_2 = km_CO_2 * t_dist. \quad (9)$$

Steps 2-4 of the approach were realized in the AnyLogistix supply chain software.

4. The results achieved

4.1. Determination of the potential logistics centers' geographical locations

The geographical locations of the potential LCs were determined with the CoG method, by giving different (1, 2, …, 10) values for the number of LCs to be generated, with the requirement that each of the locations should have at least 100,000 inhabitants.

The results of the 10 runs are given in Table 1.

Table 1. The locations of the potential LCs.

No. of LCs	Proposed solutions, GFA
1	Berlin
2	Berlin, Helsinki
3	Berlin, Helsinki, Niš
4	Berlin, Brussels, Helsinki, Niš
5	Amsterdam, Berlin, Bern, Craiova, Helsinki
6	Amsterdam, Berlin, Bern, Craiova, Helsinki, Madrid
7	Amsterdam, Berlin, Bern, Craiova, Helsinki, Madrid, Paris
8	Amsterdam, Berlin, Bern, Craiova, Dublin, Helsinki, Madrid, Paris
9	Amsterdam, Athens, Berlin, Bern, Bucharest, Dublin, Helsinki, Madrid, Paris
10	Amsterdam, Athens, Berlin, Bern, Bucharest, Dublin, Helsinki, Madrid, Paris, Rome

It is no wonder that Berlin – with its proportion of 37.9% in the total demand fulfilled by trucks – came out as the optimal location for a single LC, and it was an element of all the sets of LCs.

The average distances the products travel between the LCs and the capitals are given in Fig. 1. The orange line in the diagram shows the average distance the products had to travel from Maarssen to their destinations, namely 891 km in this baseline situation. The GFA solution with one LC (Berlin) gave 644 km for the average distance, which means a decrease of nearly 28%.

As it was expected, by increasing the number of LCs to be determined, the average distance the products travel between the LCs and the capitals decreased, especially in the beginning.

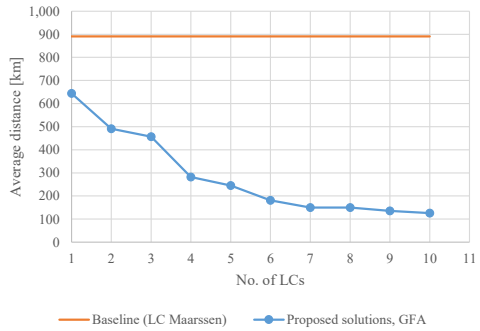

Fig. 1. The average distance the products travel between the LCs and the capitals as a function of the number of LCs.

To have some idea of the result with 10 generated LCs, the map of Fig. 2 illustrates the locations of the 19 capitals and the 10 LCs indicated by blue and red filled circles, respectively.

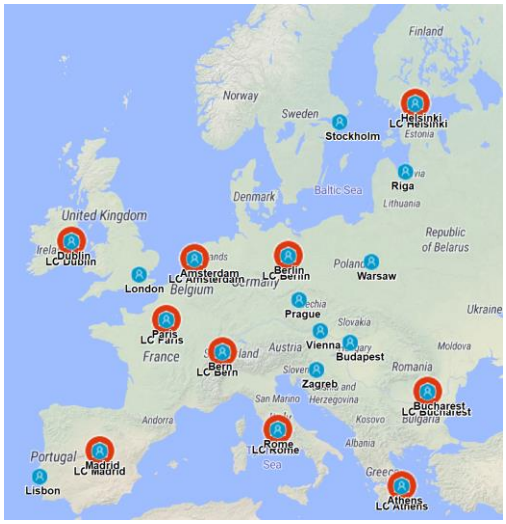

Fig. 2. The 19 capitals and the 10 generated LCs.

However, the CoG method does not take some important factors, e.g. the costs related to the LCs and to the transportation, into account. With the use of additional data, the most appropriate LCs can be selected from the set of 10 LCs, via optimization.

4.2. Cost-oriented optimization of the distribution network

In the optimization process, the following main data – some of them based on assumptions – were used:

- *Products*: computer components with a geometrical volume of 0.005 m^3 in packaged form.
- *Demands*: deterministic, historic, given for the 19 capitals, 6,883,214 pcs in total.
- *Transportation*: full truckload (FTL) policy, trucks with capacity 20 m^3 and speed 70 km/h, with cost 5 USD/km calculated with actual routes (not with straight lines).
- *Transportation-related CO_2 emission*: 1 kg/km.
- *Capacities of the LCs*: considered high enough.
- *Facility cost of the LC in Maarssen*: 8,000 USD/day.
- *Investigated time period*: 1 year.

The facility costs of the 10 potential LCs were estimated by using the gross domestic product (GDP) per capita ratios between the given country and the Netherlands (Table 2). (The GDP per capita values were taken from Eurostat.)

Table 2. Estimated daily facility costs of the potential LCs.

Potential LC location	Country	GDP per capita [€]	Ratio to NL [%]	Facility cost [USD/day]
Amsterdam	NL	41,870	100.00	8,000
Athens	GR	18,150	43.35	3,468
Berlin	DE	35,840	85.60	6,848
Bern	CH	59,970	143.23	11,458
Bucharest	RO	9,130	21.81	1,744
Dublin	IE	60,170	143.71	11,497
Helsinki	FI	37,270	89.01	7,121
Madrid	ES	25,170	60.11	4,809
Paris	FR	33,270	79.46	6,357
Rome	IT	26,860	64.15	5,132

The cost-oriented optimization showed that with the above data, one LC positioned in Berlin gave the minimum total cost. Compared with the baseline situation, the optimized distribution network resulted in 14.4%, 27.57% and 23.95% decreases in facility cost, transportation cost and total cost, respectively (Table 3). (Please note that the investigated 1-year period incorporated February 29 and therefore had 366 days.)

Table 3. Cost factors in the baseline situation and those given by the optimization.

LC location	Facility cost [USD]	Transportation cost [USD]	Total cost [USD]
Maarssen (baseline)	2,928,000	7,738,362	10,666,362
Berlin (optimization)	2,506,368	5,604,937	8,111,305

The structure of the optimized distribution network is shown in Fig. 3.

Fig. 3. The optimal structure of the distribution network.

4.3. Generation of different network structures through cost minimization under various parameters, and their comparisons

The management was interested in how the parameters of the cost factors influence the optimal structure of the distribution network, the different kinds of costs, and the transportation-related CO_2 emission. Two series of experiments were run by modifying the kilometric transportation cost and the potential LCs' daily facility costs, respectively. (While changing the daily facility costs of the potential LCs, their ratios were kept according to Table 2.) For each pair of kilometric transportation and daily facility cost values, cost-oriented optimization was performed.

The results of the optimizations were always compared with the baseline, i.e. having the original structure with one LC in Maarssen but enforcing the given values of the cost parameters.

In the first series of experiments, the kilometric transportation cost was increased stepwise starting from its original value (5 USD/km) by 2 USD/km, while keeping the daily facility cost constant at the level of 8,000 USD/day in the Netherlands as the basis.

The value pairs of the kilometric transportation cost and the daily facility cost in the Netherlands are enumerated in Table 4, together with the LC locations generated by the cost-oriented optimizations. (The first row refers to the case with the original values of the cost parameters, described in Subsection 4.2.)

Table 4. The optimal LC locations under different kilometric transportation costs and fixed daily facility cost in the Netherlands.

Transportation cost [USD/km]	Facility cost, Netherlands [USD/day]	LCs, optimization
5	8,000	Berlin
7	8,000	Berlin
9	8,000	Berlin, Paris
11	8,000	Berlin, Helsinki, Paris
13	8,000	Berlin, Bucharest, Helsinki, Paris

The influence of the stepwise increase of the kilometric transportation cost on the optimized network structures can be clearly followed in Table 4, namely more and more LCs were involved in the distribution network, decreasing this way the average transportation distance.

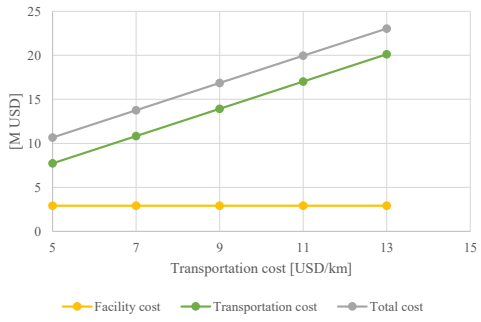

Fig. 4. Yearly facility cost, transportation cost and total cost as functions of the kilometric transportation cost, under fixed daily facility costs – baseline cases.

Having only one LC in Maarssen (baseline situation), the yearly facility cost – naturally – remained the same, while the yearly transportation and total costs increased linearly with the growing kilometric transportation cost (Fig. 4).

As to the optimized cases (Fig. 5), the yearly facility cost increased by the inclusion of additional LCs in the network. In the first two cases, the network had only one LC (in Berlin), consequently, the distances to be traveled remained the same, but because the kilometric transportation cost increased, the yearly transportation cost became higher. However, with the involvement of more and more LCs, the average transportation distance decreased. The effect of this decrease usually could surpass the influence of the increased kilometric transportation cost, and so the yearly transportation cost had a decreasing tendency. The yearly total cost increased monotonically.

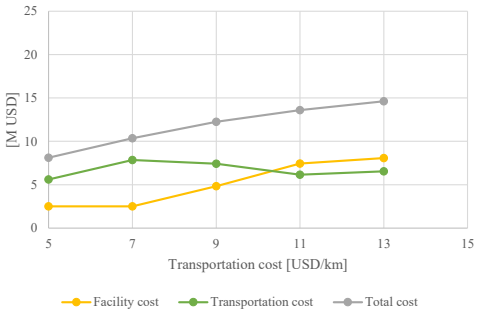

Fig. 5. Yearly facility cost, transportation cost and total cost as functions of the kilometric transportation cost, under fixed daily facility costs – optimized cases.

Comparing the yearly total cost values gained by optimization with the baseline ones (Fig. 6), it can be seen that the optimized structures clearly outperformed the baseline situation, moreover, the level of the cost reduction increased with the growth of the kilometric transportation cost.

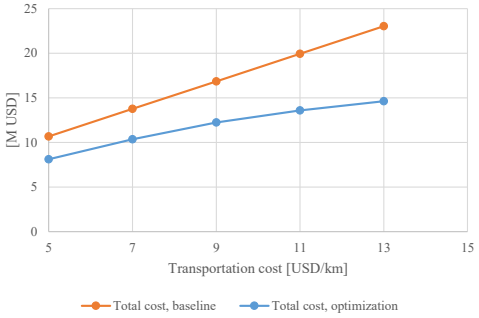

Fig. 6. Comparison of the yearly total costs as functions of the kilometric transportation cost, under fixed daily facility costs – baseline cases and optimized cases.

In parallel with this, the cost-oriented optimization brought drastic reductions in the transportation-related CO_2 emission values (Fig. 7).

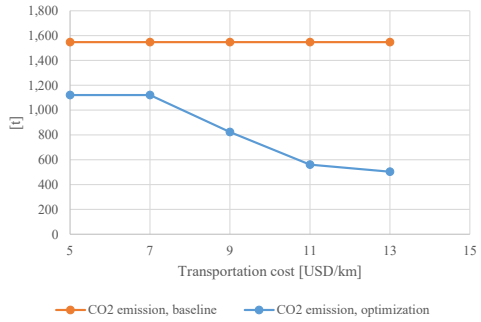

Fig. 7. Comparison of the yearly transportation-related CO_2 emissions as functions of the kilometric transportation cost, under fixed daily facility costs – baseline cases and optimized cases.

In the second series of experiments, the daily facility cost in the Netherlands was decreased stepwise by 1,000 USD/day starting from its original value (8,000 USD/day), and the kilometric transportation cost was kept constant at the level of 5 USD/km (Table 5). The table also illustrates that the lowering of the daily facility cost in the Netherlands (and in the same ratio the daily facility costs of the potential LCs in other countries) can make the involvement of additional LCs remunerative.

Table 5. The optimal LC locations under different daily facility costs in the Netherlands and fixed kilometric transportation cost.

Transportation cost [USD/km]	Facility cost, Netherlands [USD/day]	LCs, optimization
5	8,000	Berlin
5	7,000	Berlin
5	6,000	Berlin
5	5,000	Berlin, Paris
5	4,000	Berlin, Helsinki, Paris

Due to the page limitation of the paper, the results of the second series of experiments are not described here in detail.

Considering all the optimization experiments, four different structures came out, with one, two, three and four LCs. Fig. 8 shows the version with four LCs, including the capitals to be served and the routes of transportation.

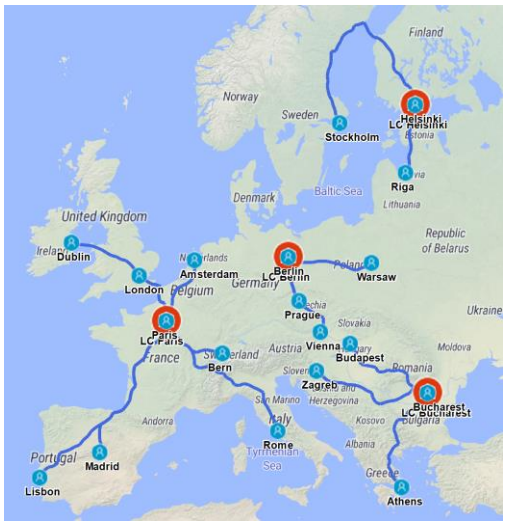

Fig. 8. The optimal structure of the distribution network with four LCs.

5. Conclusions

The project with the global manufacturing company offered a valuable opportunity to test – at least partly – the approach introduced in [12] in an industrial setting. The application of GFA followed by optimization – in this case by cost minimization – led to a network structure that, according to the available data, proved to be more efficient than the network run by the company.

Moreover, the deeper analysis highlighted the dependence of the optimal network structure on the parameters of the cost factors considered. Those results for example, which indicated the benefits of opening more LCs, and this way shortening the average distance the products have to travel in case of higher transportation costs, e.g. fuel prices, gained special relevance in the energy crisis of our time.

The results of the investigations, presented to the representatives of the company, gave also important insights into the environmental load caused by the transportation in the different network structures, and can be considered when the management aims at a more environment-friendly operation of the distribution network.

The project described here satisfied the company and paved the way for further ones outside the scope of the paper.

Acknowledgements

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