A Green logistic model for both cost and emission minimization under inventory policies

Bachelor Thesis Econometrics and Operational Research - Logistics

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Abstract

This report aims to find an optimal supply chain network with 22 European distribution centers for two types of refrigerators produced in China. The supply chain will be optimized in such a way that transport costs and emission costs are minimized and inventories are perfectly located. First a model is created where only a truck is used, secondly the train will be introduced and after that the barge will be included. This is followed by the implementation of inventories and safety stock. It is analyzed at which place, distribution center or demand region, the safety stock should be located. In the final model the costs of emissions are incorporated to create a green supply chain.

Keywords: optimization, supply chain, costs CO2 emission, transport costs, environment, AIMMS

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1 Introduction

Environmental issues have become increasingly important over the years. In Europe the European Union sets out the emission standards for all transportations modes. The European Commission (the executive body of the European Union) published several reports and action plans such as ''Freight Transport Logistics Action Plan''(European Commission, 2007), ''Greening Transport'' (European Commission, 2008a), ''Strategy for the Internalization of External Costs'' (European Commission, 2008b), ''A Sustainable Future for Transport: towards an Integrated, Technology led and User friendly System'' (European Commission, 2009). However, one of the most influential policies is the Kyoto protocol, which is mainly focussed on road and freight transport (Chapman, 2007). All these reports, actions plans and policies support the use of environmental friendly transportation modes and other economic instruments as taxes. In this research the focus is on the affect of environmental issues on the design of the supply chain.

Since the global trade grew from 57.5 billion USD to 3600 billion USD (Tavasszy et al., 2011) between 1948 and 1992, the supply chain has developed to an extensive and complex network that connects production locations with demand regions (DR) all over the world. However, the increase of the global trade resulted in an increase of global transport volumes. The transport, mainly freight transports, leads to a release of large amounts of emissions.

Though environmental issues and related cost of emissions are considered, cost minimization of supply chain operations is undeniably the most important objective for supply chain network design today (Mallidis et al., 2012). Therefore this study aims to provide a cost and CO2 optimization for refrigerator supply chain to the whole EU, without assumptions limiting the number of possibilities. This implies the lack of a restriction on the amount of ports, distributions centres (DCs) and DRs. Two models of Haier refrigerators are transported namely HT21TS77SP (big model) and HNSE032 (small model).

Since inventories are related to the number of DCs in the supply chain; more DCs means a larger amount of inventory in total which contributes to higher costs, but on the other hand more DCs generates a quicker response to the retail stores which provides a higher service level. Hence, additionally to the cost minimization and the design of a green supply chain, this study includes a better[1] modelling of inventories in the model and assess its effect on the optimisation.

Finally this study provides an extensive sensitivity analysis of the input parameters and the effect of various data and model assumptions.

This research will combine the minimization of costs, CO2 emission and incorporate an efficient inventory planning. To do so, this study is structured as follows: in section 1 previous research is evaluated and the main findings of this research are discussed. Followed by an explanation why further research is required. In section 3 a description of the obtained data is given. Section 4 describes the different objective models. Section 4 consists of 5 models, for each model the results are given, a sensitivity analysis is provided and finally followed by a conclusion. In section 5 a general conclusion of all models is given.

[1] better than obtained from research in the seminar Seminar ''Supply Chain Management and Optimization''

2 Literature review

2.1 Previous research

Related research can be classified in three categories:

1. *Research related to supply chain network design*
   The design of a supply chain network incorporates decisions among the number, locations, and capacities of the DCs. Besides, the company must make a selection of different intermediate parties, as suppliers and freight forwarders, in such a way that the goals regarding to cost and product delivery time are met (Klibi et al., 2010). After that, an important choice is made about the use of transportation modes and the cargo volumes transported (*Melo, Nickel, Saldanha-da-Gama, 2009)*.

2. *Research related to a green supply chain network*
   Environmental issues is become increasingly important in recent years, this implies that only recent research is provided about supply chain management considering the environment. Most recent study is given in Dekker et al. (in press). A first classification of this research efforts include green product design and manufacturing studied by Luh et al. (2010), Chu et al. (2009), and O' Brien, 1999, green transportation and distribution studied by Neto et al. (2008), Li et al. (2008), Ramudhin et al. (2009), Iakovou et al. (2010), green warehousing studied by Emmet and Sood (2010) and Mckinnon et al. (2010)

3. *Research related to supply chain network and related inventory planning*
   Chung and Wee, 2010, Chen and Monahan, 2010 and Ahiska and King 2010, Wee et al 2011 and Hsueh, 2011) providing research related to a tactical policies related to inventory management.

However, several researchers have already tried to evaluate the environmental impact of freight transportation, mainly on CO2 emission. They proposed different strategies to mitigate CO2 emission (Liao et al., 2011; Chapman, 2007; Hickman et al., 2011).

In this research is mainly focussed on two articles both provided by Mallidis, Dekker and Vlachos. Both Mallidis et al. (2012) and Mallidis et al. (2014) incorporated the literature stated above. In the first article, ''The impact of greening on supply chain design and cost: a case for a developing region'', a strategic –tactical decision support model is developed to assist manager in evaluating the impact of environmental issues, related to transportation emissions regionally. This model is analysed for a supply chain with two ports, two DCs and four DRs. The second article, "Design and planning for green global supply chains under periodic review replenishment policies '', describes a green logistic model for analysing the effect of both cost and CO2 emissions minimisation. The paper describes a methodology to find the optimal order delivery frequencies and stock levels reserved at each node in such a way that is minimize either total logistics cost or CO2 emissions.

2.2 Conclusion from previous research

In Mallidis et al., (2012) the study was based on the optimization of the supply chain based on CO2 and PM emission. Results of this shows that optimization based on CO2 emissions does not increase the supply chain network costs largely since cost and CO2 emission objectives are often related. Companies could achieve a good balance between cost en CO2 emissions by implementing a CO2 emission minimization policy. However, optimization based on other emissions (e.g. fine dust) does increase the cost of the supply chain significantly. Reducing others emissions is only achieved by the purchase of expensive newer trucks. A solution for these cost increase may be solved by the deployment of more electric rail transportation on existing routes.

The result of the analysis in Mallidis et al. (2014) indicate that strategic network design and tactical inventory planning decisions can be significantly affected when environmental objectives are considered. On a strategic level, the optimum network structure with respect to costs and CO2 emissions lead to an increased number of independent regional DCs. However, more DCs increases inventory costs. On a tactical level, the inclusion of CO2 emissions minimization objectives results in lower order delivery frequencies compared to those prescribed by cost minimization, which results in lower transportation costs and CO2 emissions on one hand and higher holding costs and backorder costs on the other. Lower order delivery frequencies might increase the probability of stock outs at retail stores, the cycle service levels of products at the retail stores and satellite DC are reduced under CO2 emissions optimization criteria.

2.3 Limitation of previous research

In current research the optimization of the supply chain was solved with Excel. The economists were not able to use other mathematical programs like Matlab, AIMMS and Java. Since Excel could not solve large problem, the research was limited because the small region which was examined and therefore not globally applicable. By using other mathematical programs, the model can be extended and solved in such a way that it is globally applicable.

2.4 Further research

In this study both Mallidis et al. (2012) and Mallidis et al. (2014) are combined to design a supply chain for the transportation of refrigerators from China to whole Europe. For this research the model presented in Mallidis et al. (2012) is extended to more ports, DCs and DRs. Furthermore, the methodology provided by Mallidis et al. (2014) is complicated, therefore this research will found a simplified methodology to implement inventories. However, in Mallidis et al. (2014) the model is only for two warehouses applied, this model will be extended for multiple warehouses.

3 Model description

3.1 Network design

The supply chain starts by the Chinese refrigerator manufacturer. From Shanghai, for simplicity it is assumed that shipment is only possible from Shanghai, the manufactured goods will be transported by ship to Europe. The six different ports which are used in Europe are: Rotterdam, Trieste, Hamburg, Marseille, La Havre and Constanta.

From the different ports in Europe the refrigerators can be transported by truck, train or barge to the eight different DCs namely Venlo, Paris, Frankfurt, Berlin, Prague, Warsaw, Budapest and Bucharest. Finally the refrigerators have to be delivered to the 22 different DRs. This transportation occurs only by truck or train.

3.2 Objective

The objective of this study is to design green supply chain model which minimizes both cost and emissions. This section describes the different models to find this optimal supply chain model. Each model consist of an objective functions and several constraints. The first model is a general model, which will be extended to a final model. Finally, this leads to a model with different transport modes and the inclusion of inventory and emissions.

In the first model it is assumed that only trucks can be used for transportation between the ports and the DCs and the DCs and the DRs. In the second model the train is added as transportation mode. In the third model the barge is added. Since inventory causes costs as well, this is implemented in the fourth model. In the last model, the costs of emissions are incorporated to design a green supply chain.

3.3 Solver

The models are implemented in AIMMS (Advanced Integrated Multi-dimensional Modeling Software). AIMMS is an algebraic modeling system with the possibility to easily implement advanced mathematical models, data connections with databases and graphical user interfaces. In this research the student version of AIMMS 3.13 with CPLEX 12.5.1 as solver was used for our programming model. Calculation times for the MIP model are in the order of a few seconds.

4 Input Variables

The data is provided by earlier research done in the course '' Seminar Supply Chain Management and Optimization'', which is a master course of the study economy. In this course the case was also about transportation of refrigerators from China to Europe. This section set outs the data provided by the course.

4.1 Demand prediction

The prediction of the demand for each region was already calculated and is given. A linear regression model was used to predict the demand in 2022. This demand is used and therefore optimization is for the demand in that year.

Using this demand the necessary containers can be calculated to transport all refrigerators to Europe. Two types of refrigerators are transported, a small and a big model. We assume that the refrigerators are equally distributed between the containers and each container contains 56 refrigerators.

4.2 Distances

For the given ports, DCs and DR the distances between all connections are given. These distances from Shanghai to all ports in EU were calculated by using the Port to Port distance calculator (http://www.searates.com/reference/portdistance/). The distances are stated in table 4.2.

Table 4.2: Port distance

Port EU	Distance from China (km)
Rotterdam	22222
Lisbon	17429
Trieste	18098
Hamburg	22737
Marseille	18609
Le Havre	21750
Constanta(port)	17537

The distances of the transportation per train were calculated with the data from Google Maps (https://www.google.nl/maps/preview). It is assumed that the distances for train, truck and barge are the same. This is a good proxy since most of the railroad and waterways are next to the highways. If a DC and the DR are in the same city, it is assumed that the distance is 15km. The DC is most times not in the centre city.

4.3 Cost of transportation

Besides the distances, the costs are given for each mode. The transport cost from China to an entry point (port) consists of the transport costs to the port and the port handling costs. For each port both shipping line and port handling costs are provided. These costs are stated in table 4.3.

Table 4.3: Port costs

Ports	Transport Cost (from Shanghai to each port) (€/container)	Terminal handling costs (€/container)
Rotterdam	2680	140
Lisbon	3160	180
Trieste	3160	180
Hamburg	2680	160
Marseille	3160	180
La Havre	3160	180
Constanta	3360	180

Next to the shipping costs the truck cost, these costs are 2€/km/container. Furthermore the rail costs are provided. The rail costs consists of a variable costs including the transporting of a 40ft container to its destination's rail depot and returning the empty 40ft container and a fixed costs including the discharge from wagon and a loading on truck cost per 40 ft container at the rail freight depot as the loading of the returning empty 40ft container on the wagon (Mallidis et al., 2012). The variable costs are 1€/km/container and fixed costs are 200€/container. Finally the barge costs are provided. Also the barge costs consists of a variable rate of 1, 5€/km/container and fixed rate of 120€/container.

4.5 Emissions

For all modes; truck, rail and ship, the emission is provided. The emissions for the different modes are calculated with the STREAM-model (Boer et al, 2011). This model takes into account different variables. The emission is given per gCO2/km/ton and is based on average emissions for container transport. It is assumed that the total load only depends on the load inside the container. The emission for each mode is stated in table 4.5.

Table 4.5: CO2 emission for different modes

Parameter	Truck	Train	Ship	**Unit Measure**
CO_2 Emission	62	29	19	g/t/km

CO_2 emissions can be transformed into cost values by multiplying total emissions with the unit price of tCO_2 The Carbon Dioxide Price is 40€/tCO2[2].

4.6 Cost opening DC

The cost for opening a DC is a function of the warehouse capacity (Mallidis et al., 2012). The cost per container is not constant but it depends on the container throughput. The cost rates, in terms of euro per container per day, can be formulated with $f(c)$ as follows:

$$f(c) = c * 0.267 + 4250.5 \qquad (1)$$

where *c* is the capacity (container per day) of the distribution center and *f(c)* is the fixed cost per day which is dependent on the capacity.

4.7 Lead time

For every mode the lead times differs. The lead time of the shipment from Shanghai to Europe don't have to be calculated and is assumed to be 30 days. The lead time of 30 days has to be added to the

[2] Luckow et al, 2013, 2013 Carbon Dioxide Price Forecast, http://www.synapse-energy.com/Downloads/SynapseReport.2013-11.0.2013-Carbon-Forecast.13-098.pdf

lead time to the DC to get the total lead time from Shanghai to the DC. The lead time from ports to DC and from DC to DR is depended on the speed of the transportation mode. For each transportation mode and each connection in the supply chain the required amount of time is calculated to deliver items from origin to destination using the average speed of each transportation mode. The time needed for delivering goods can be considered as the lead time. The average speed of the truck, train and barge is respectively 60km/h, 10km/h and 20km/h[3].

Since the model is generated per year or week, the lead times are adjusted to the speed per year or week. To do so, the speed per year and per week is the average speed times 8736 (24*7*52) and times 168(24*7) respectively.

4.8 Holding costs

The total holding costs consists of the pipeline stock downstream and upstream of the DC, the costs depend on whether the transportation is done by truck or train and its lead time. The costs of the stock in pipeline are dependent on the value of the container including the load and the holding rate$r$. The holding rate is assumed to be 0.1€/year the value of the container is amount of refrigerators in the container times the value of the containers.

4.9 Safety stock

Since safety stock (SS) is very important in dealing with unexpected situations, like an enormous demand increase or bad weather conditions, the SS has to be incorporated in the model as well.
For the SS a cycle service level of 95% is used whit a related z value of 1.645. The formula for the SS is provided in (2):

$$SS = z * \sigma\sqrt{LT} \qquad (2)$$

$$z = 1.645$$

$$\sigma = demand\ during\ lead\ time\ i$$

The SS can be hold at the two different places, the DC or the DR. Therefore, four different SSs have to be calculated.

4.10 Cargo weight

The cargo weight is the weight of the goods in the container. Each fully container contains 56 refrigerators, both types equally distributed. The average weight of the two types is 79, 7 kg. This results in an average cargo weight of 56*79, 7 = 4463, 2 kg per container. To calculate the cargo weight of the demand in a certain region, the cargo weight has to be multiplied by the demand of containers of that region.

[3] This is an average and was wrongly given in the assignment, I will adjusted this later in the coming weeks.

5 Mathematical Models

5.1 Model 1

In this model only the use of trucks is allowed between all connections in the supply chain. Besides, it is assumed that multiple DCs could be opened to create an optimal supply chain. Furthermore, all ports can be used. Ports already exist and could therefore better be used.

This mathematical model consists of different sets, parameters and variables. A clear overview of the sets and parameters used are stated in **Appendix A and B**.

Sets

I: Set of demand regions.
J: Set of candidate DC locations.
K: Set of ports.

Parameters

c_{kj}^{truck} : unit cost of transporting a single container from port *k* to DC *j* by truck (€/container).
c_{ji}^{truck} : unit cost of transporting a single container from DC *j* to demand region *i* by truck (€/container).
FC_j : fixed cost of opening a DC at the candidate location j (€/year)
VC_j : variable cost of opening a DC at the candidate location j (€/container/year)
PC_k : cost of using port *k* (€/container)
D_i : demand of region *i* (container/year)
A_{truck} : fixed cost of transportation by truck (€/container)
M : a very large constant.
DY : total days in a year

Variables

x_{ji}^{truck} : 1 if truck is used between DC j and demand point *i* 0 otherwise.
y_j : 1 if a DC is opened to candidate location *j*, 0 otherwise.
Q_{kj}^{truck} : amount of container transported from port k to DC j by truck.

Model

$$\min \sum_{k\in K} \sum_{j\in J} Q_{k\,j}^{\,truck} (c_{kj}^{truck} + A_{truck}) + \sum_{j\in J} \left(\sum_{i\in I} D_i \big(c_{ji}^{truck} + A_{truck}\big) x_{ji}^{truck} \right) + DY \sum_{j\in J} y_j\, FC_j + DY \sum_{j\in J} VC_j \sum_{k\in K} \big(Q_{kj}^{truck} \big) + \sum_{k\in K} PC_k \sum_{j\in J} \big(Q_{kj}^{truck} \big) \tag{3}$$

$s.t.$

$$\sum_{j \in J} x_{ji}^{truck} = 1 , \qquad \forall\, i \in I, \tag{4}$$

$$\sum_{i \in I} x_{ji}^{truck} D_i \leq \sum_{k \in K} Q_{kj}^{truck} , \qquad \forall\, j \in J, \tag{5}$$

$$\sum_{k \in K} Q_{kj}^{truck} \leq y_j * M, \qquad \forall j \in J,. \tag{6}$$

$$x_{ij} \in \{1,0\}, y_j \in \{1,0\}, Q_{kj} \geq 0, \qquad \forall i \in I, j \in J, k \in K. \tag{7}$$

In this model the objective function (3) has to be minimized. The objective function consists of several cost terms. The first term defines the transportation costs from the ports to the DCs. The second defines the transportation costs from the DCs to the DRs. The third term defines the fixed costs of opening a DC and the fourth term defines the variable costs of opening a DC. The last term defines the cost of using a port; this includes the handling and transportation costs.

In this model multiple constraints are added to the model. Constraint (4) makes sure that each region is served by exactly one DC. Constraint (5) is called the flow conservation constraint. This constraint makes sure that the inflow of refrigerators (right hand side of the constraint) in the DC is equal or larger than the outflow of the DC (left hand side). Constraint (6) makes sure that if there is outflow of the DC, the distribution centre has to be opened. Constraint (7) defines the decisions variables used in the model.

5.1.1Results

Although, it is allowed to use all ports, we will not use the all the ports. The ports which will be used in the optimal solution are: Rotterdam, Trieste, Hamburg and Constanta. The total cost of using this ports are €1.162.750.960,00. From these ports all refrigerators are transported to the DCs. The DCs which will be opened are: Venlo, Paris, Berlin, Bucharest and Budapest. The cost of opening a DC consists of variable and fixed costs. The total costs (fixed + variable) of opening these 5 DCs are € €7.757.162.5+€39.639.918,71=€47.397.081,21.Besides the opening costs for DCs, costs are made for transporting the refrigerators form the port to the DC. The total costs are € 214.250.046,00 From the DCs all refrigerators will be further transported to the DRs. In the **Appendix C** an overview is given of which DC exactly serve which region. Because of constraint (4), it is not allowed in this model that a region can be served by multiple DCs. The total costs of transporting the refrigerators to DRs are € 451.585.960,80. Finally, the overall cost of the supply chain for transporting the refrigerators from China to all DRs in Europe are €1.875.984.048,00. In the table 5.1.1 the percentages of the total costs are given of all 5 terms mentioned in (3).

Table 5.1.1 Costs and percentage of model 1

Costs of	Term	Costs (€)	Percentage (%)
Port	5	€ 1.162.750.960,00	62
Opening DC	3-4	€ 47.397.081,20	2,5
Transport Port-DC	1	€ 214.250.046,00	11,4
Transport DC-DR	2	€ 451.585.961,00	24,1
Total		**€ 1.875.984.048,00**	

5.1.2 Sensitivity analysis

5.1.2.1 Opening One DC

The network can consists of one of multiple DC. In the optimal solution five DC are opened, but how much will the costs increase if one DC is opened. To make sure that only one DC is opened, an extra constraint has to be added to the model:

$$\sum_{j \in J} y_j = 1 \tag{8}$$

Implementing this constraint will result in opening the DC of Venlo. The total costs for transporting the refrigerators from China to Europe will be €2.004.317.776.

5.1.2.2 Increasing cost port

Rotterdam is having the lowest port costs among all other ports. Therefore, we will determine for which costs the port of Rotterdam (PoR) will not be beneficial over other ports.

Therefore the costs for the port are increased to determine if the outcome will change significantly. It will be calculated for which shipping cost, the PoR is less efficient and other ports can be better used.

Currently, the PoR is serving the DCs of Venlo and Paris. These DCs had to be served by another port, if Rotterdam is not be used anymore. Logically, this will be the nearest ports after Rotterdam. For Venlo this will be Hamburg and for Paris this will be La Havre. However La Havre is closer to Paris, shipping cost are higher than in Rotterdam. I will calculate the breakeven point for which costs the PoR will not be used anymore. To do so, both port costs and transportation costs to the DCs has to be calculated. I will set the ''new situation'' for both Venlo and Paris equal to the old situation where the PoR was used.

Venlo:

amount transported to Rotterdam* port cost + amount transported to Venlo*transport cost
=
amount transported to Hamburg∗ port cost + amount transported to Venlo∗transport cost (9)

209047*2840+209047*840=209047x+209047*344

x=3336

Paris:

amount transported to Rotterdam for Paris* port cost + amount transported to Paris*transport cost
=
amount transported to La Havre for Paris * port cost + amount transported to Paris*transport cost (10)

82367*3340+82367*394=82367x+82367*890

x=2844

The PoR will not be used for transportation to Paris and Venlo if the shipping costs are increasing to €2844/container and €3336/container respectively. Instead the port of La Havre and the port of Hamburg will be used. I also manually increased the port cost, to see what happened with the total amount of refrigerators transported through the PoR. Slowly, the goods will be transported via other port and the amount of goods transported by the PoR will decrease. Finally all goods are transported by ONE other port. In our case this are La Havre and Hamburg. Logically, the cost of the supply chain increases due to higher port costs.

5.1.3 Conclusion

In the optimal solution four ports are used; Rotterdam, Trieste, Hamburg and Constanta. The DCs which are opened are: Venlo, Paris, Berlin, Bucharest and Budapest. Transportation occurs by truck between the different connections points. A clear overview is given in **Appendix C**. The total costs of this model are €1.875.984.048,-

In the sensitivity analysis it is determined what the effect is opening one DC. The DC which will be opened is Venlo. Opening one DC will lead to a costs increase of 7% comparing to the model with multiple DCs. Although the total costs increase, the costs of opening a DC decrease from €47.397.081,20 to €41.191.351, - , which is a 13% decrease. This is due a larger distance from the port to the DCs and from the DCs to the DRs most times. Consequently, only the PoR will be used, since this is the nearest port to Venlo.

It could be seen from table 4.1 that most costs are caused by using ports. Therefore, another sensitivity analysis was performed to determine the influence of changing the shipping costs on the current results. The shipping costs of the PoR were increased and it was determined for which costs the port was not be used anymore. It turned out that the PoR will not be used for transportation to Paris and Venlo if the shipping costs are increasing to €2844/container and €3336/container respectively.

5.2 Model 2

In this model it is assumed that both transportation modes, truck and train, can be used. A train is used if the distance from port to DC is less than 200 kilometres. This is because of the cost of using a truck is 2€/km/container and for a train 1€/km/container and fixed costs of 200€/container. This results in the following equations, where the amount of containers can be ignored because they are for both the same

$$2x = 200 + x, \qquad (11)$$

where x is the total kilometres of transporting. The outcome of this equation is x = 200, which means that for less than 200 kilometres it more beneficial to use a truck.

To implement the train in the model three parameters and one decisions variable. The rest of the assumptions made in model 2 remain unchanged.

<u>Addition of parameters:</u>
c_{kj}^{train}: unit cost of transporting a single container from port *k* to DC *j* by train (€/container).
c_{ji}^{train}: unit cost of transporting a single container from DC *j* to demand region *i* by train.
A_{train}: Fixed cost of transportation by train (€/container).

<u>Addition of decision variables:</u>
x_{ji}^{train}: 1 if train is used between DC j and demand point *i* 0 otherwise

The extended model can be found in the **Appendix D**.

5.2.1 Results:

In this model, an optimal supply chain is generated by using four ports: Rotterdam, Trieste, Hamburg and Constanta. These are the same ports as in model 1. In this supply chain design all DCs are opened. Transportation from port to DC, occurs ones per truck between Rotterdam and Venlo, since this is the only connection, from the ports we use, which is less than 200 kilometres. The remaining transport between ports and DCs occurs by train.
From the DCs to DRs, a truck is used when the DCs is in the same city as the DR is and between Venlo and Eindhoven. Again, this is because the distance is less than 200 km in both situations. For all other connections the train is used. An exact overview of which port serves which DC and which DC serves which DR and whether this occurs by train or truck is given in **appendix E**.

In the table 5.2.1 the percentage of the total costs are given of all 5 terms mentioned in (3)

Table 5.1.1 Costs and percentage of model 2

Costs of	Term	Costs (€)	Percentage (%)
Port	5	€ 1.162.750.960,00	69
Opening DC	3-4	€ 52.051.379,00	3.1
Transport Port-DC	2	€ 213.878.831,00	12.7
Transport DC-DR	1	€ 248.835.523,00	14.8
Total Costs		**€ 1.677.516.693,00**	100

To be sure if the model is right and it is indeed more expensive to use a train if the distance is less than 200 km, a calculation is made with some of the results. From the table in Appendix E is could be seen that a truck is used to transport containers from Venlo to Eindhoven. The distance between Venlo and Eindhoven is 57, 2 km. Transportation by truck costs: amount of containers * 2€/km = 26.798*2*57,3=€3.071.050,80. Transportation by train costs: amount of containers * (1€/km+200) = 26.798*(57,3+200): =€6.895.125,40. It is true that transportation by train is indeed more expensive.

5.2.2 Sensitivity analysis

5.2.2.1 One DC

To implement one DC in the model, the same constraint (7) as in model 1 will be added to the model.

The DC which will be opened is again Venlo and the port which is used is Rotterdam. All containers will be transported by truck, because of the small distance. From Venlo only Eindhoven is served by truck, all other DRs are served by train. The total cost of this supply chain is €1.743.760.771.

5.2.2.2 Higher cost port of Rotterdam

Currently the PoR is serving Venlo by truck and Frankfurt and Paris by train. If these DCs cannot use Rotterdam anymore, they have to be served by other ports nearby. The nearest port after Rotterdam is Hamburg, for both Venlo and Frankfurt. For Paris, la Havre is even closer to Rotterdam. The low port cost in Rotterdam compensating the high transport cost from Rotterdam to Paris, 1736 €/container per train instead of 449 €/container per truck.
If the cost of the PoR risen a little, first a part of the containers which were transported from Rotterdam to Venlo will now be transported via Hamburg to Frankfurt and Berlin. The containers are divided among these DCs. In the original result 180974 containers are transported to Venlo by truck, now 26597 containers are added to the transport from Hamburg to Frankfurt and 38103 containers are added to the transportation to Berlin. Almost all DRs which were first served by Venlo are now

served by Frankfurt and Berlin. Only a part of the containers is still transported by truck to Venlo and the other part is transported by train to Londen. For both DR holds that if they are served by Frankfurt or Berlin the distance increase, for other DRs the distance decrease if they are served from Frankfurt or Berlin. Therefore, the shipping costs have to be more increased for London en Venlo. Once the port costs in Rotterdam are raised to €3115 the PoR will not be used anymore. Venlo is served by train from the port of Hamburg. From there London en Eindhoven are still served by Venlo.
I also calculated the amount of cost for which Frankfurt and Paris will use another port. The same calculation is made as in model one. For Paris I compared the transportation cost and shipping cost of using la Havre instead of Rotterdam and for Frankfurt I compared the transportation cost of using Hamburg instead of Rotterdam.
If the cost of the PoR risen to €2867, Frankfurt will not be served by Rotterdam anymore. Frankfurt will now be served from Hamburg by train. If the costs rise further to €3089, Paris will be served by La Havre. However, the transportation mode will change from train to truck, because the distance from Paris to La Havre is less than 200 kilometers the train is more beneficial.

5.2.3 Conclusion

In the optimal solution four ports are used; Rotterdam, Trieste, Hamburg and Constanta and all DCs are opened. Transportation occurs per train and truck between the different connections points. A clear overview is given in **Appendix E**. The total costs of this model are €1.677.516.693,-

Introducing the train leads to a costs decrease of 11% compared to the model where only the truck was allowed.

Calculations confirm our analysis that a truck is used when the distance between two connections points is less than 200km.

In table 5.2.3 the costs for both models, one and multiple DCs are stated.

Table 5.2.3: Costs for one DC and multiple DCs

Costs of	Cost one DC	Costs € original	Percentage
Port	€ 1.147.037.820,00	€ 1.162.750.960,00	-1.4%
Opening DC	€ 41.191.351,00	€ 52.051.379,00	-20.9%
Transport Port-DC	€ 139.922.344,00	€ 213.878.831,00	-34.6%
Transport DC-DR	€ 415.609.256,00	€ 248.835.523,00	67.0%
Total Costs	**€ 1.743.760.771,00**	**€ 1.677.516.693,00**	**3.9%**

It could be seen that the total costs will increase with 4% if one DC is used. The increase in costs in caused by high transportation costs from the DC to the DRs. Some DRs are far located from the DC Venlo and therefore the costs are very high. Table X showed also that the other costs decrease, this is because one port is used, Venlo is close located to Rotterdam and instead of multiple DCs there is only DC opened.

Again most costs are caused by shipping. Therefore, the influence of the shipping costs is again analysis. If the costs will rise to €2867, Frankfurt will not be served by Rotterdam and served by Hamburg by train. If the costs rise further to €3089, Paris will be served by La Havre instead of Rotterdam.

5.3 Model 3

In this model the barge can be used as well. The assumption made in model 2 still holds. Barge transportation is only possible between the PoR and the two DCs; Venlo and Frankfurt. For the implementation of the barge two parameters and one decision variable have to add to the model.

Since, it is not possible to use a barge for all other connection, the cost for these connection are set very high in such a way that is always more beneficial to use a train or truck

Addition of parameters:
c_{kj}^{barge}: unit cost of transporting a single container from port *k* to DC *j* by barge (€/container).
A_{barge}: Fixed cost of transportation by barge (€/container).

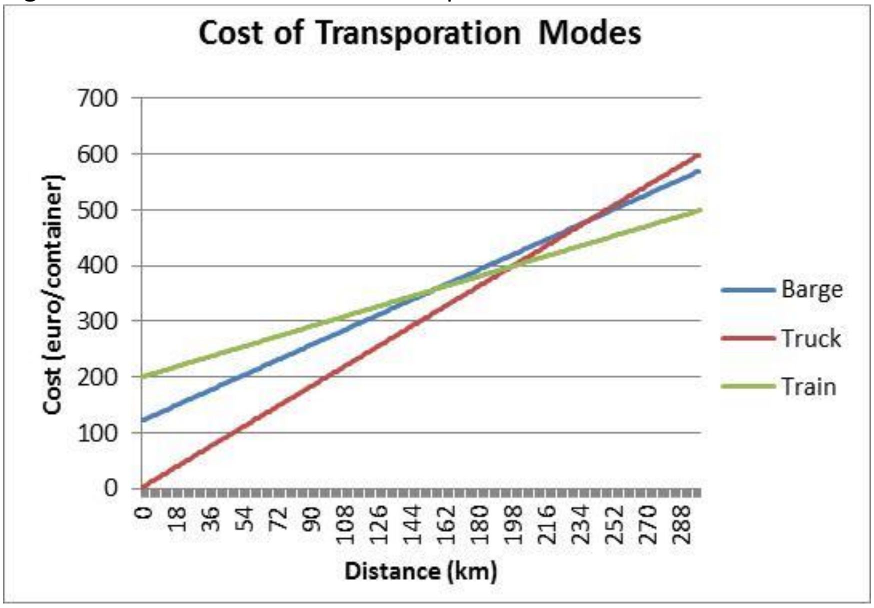
Addition of decision variables:
x_{ji}^{barge}: 1 if barge is used between DC j and demand point *i* 0 otherwise

The extended model can be found in the **Appendix F**.

5.3.1 Result

In figure 1 the cost function for each transportation mode is given. From this figure it can be seen that if the distance between two connection, e.g. port to DC, is larger than 160 kilometers it is more beneficial to use a train instead of a barge. But it previous analysis it could be seen that for less than 200 km the truck is preferred over train. If the distance is larger than 240 kilometers, a barge is preferred over a truck. It is already been said that a train is less expensive from 200 kilometers and the train could be better used. To summarize, for less than 200 km the truck is used and for over 200km the train is used. The barge will never be used in this model and he results remain unchanged compared to model 2. To check whether it is indeed true that the barge is not beneficial a calculation is made with the results of model 2.

Figure 1: Cost functions of each transportation mode



In the model 180974 containers are transported by truck. The total costs of this transportation are (180974*2*172) = 62255056. The cost of transportation by barge, considering the same amount of containers, are (180974*1.5*172)+(180974*120)=47234214+21716880=68951094. From this calculation is can be concluded that transportation per truck is less expensive.

Transportation from Rotterdam to Frankfurt containing 28073 containers which are transported by train. The costs for transportation are (28073*1*449) + (28073*200) = 126047777 + 5614600 = 17679377. The costs of transportation from Rotterdam to Frankfurt per barge are (28073*1.5*449) + (28073*120) = 18907165.5+3368760=22275925.5. Transportation by train is still cheaper than by barge, also in this case the barge will not be used.

5.3.2 Sensitivity analysis

Since the model did not change comparing to model 3, the results of increasing the cost of the PoR and using one DC will be the same. However, it could be interesting to know for which costs barge might be used.

The costs of barge transportation consist of variable and fixed cost. Assuming that the variable cost cannot be changed, it might be possible to lower the fixed costs. E.g. less staff, cheaper staff etc.
An equation can be made to comparing the current situation including a truck or train and using a barge. The variable costs are assumed to be unknown.

Train vs. Barge (for Frankfurt)

$$(28073 * 1 * 449) + (28073 * 200) = 28073 * 1.5 * 449) + (28073 * \mathrm{x})$$

$$18219377 = 18907165{,}50 + 28073x \tag{12}$$

$$28073x = -687788{,}5$$

Even when fixed costs are zero, the barge will not be used. The variable costs must be adjusted too. Therefore, we set x=0 and introduce a new variable y for the variable costs.

$$(28073 * 1 * 449) + (28073 * 200) = 28073 * \mathrm{y} * 449) + (28073 * 0)$$

$$y = 1.45 \tag{13}$$

For variable cost of 1.45 €/container and fixed cost of zero, the barge will be used

Truck vs. Barge (for Venlo)

$$180974 * 2 * 172 = 180974 * 1.5 * 172) + (180974 * \mathrm{x})$$

$$62255056 = 46691292 + 180974x$$

$$180974x = 15563754 \tag{14}$$

$$x = 86$$

From equation (14) it can be concluded that if the fixed costs are less than 86 euro/container the barge will be used.

The results are shown that barge will not be used, therefore for further analysis the model without barge is used.

5.4 Model 4

In this model the inventory and the safety stock is included. In a supply chain goods a constantly transported and is takes time to deliver goods to the DCs and the DRs. The costs of transportation are calculated with the pipeline stock downstream and upstream of the DCs. To deal with unexpected circumstances, there is a SS as well. The SS can be located at the DC or at the DR. The lead time to the DR is very small and since the SS is dependent on the lead time, the SS which will be located at the DR is also very small. The SS will not influence the supply chain a lot, because the costs related to that SS is also very small. As a result the SS will be located at the DC.

As already mentioned, the SS is dependent on the lead time. This is the reason 5 new parameters have to add to the model.

$LT_{j,i}^{truck}$: lead time in weeks from DC *j* to demand region *i* given that items are transported by truck.
$LT_{j,i}^{train}$: lead time in weeks from DC *j* to demand region *i* given that items are transported by train.
$LT_{j,i}^{truck}$: lead time in weeks from port *k* to DC *j* given that items are transported by truck.
$LT_{j,i}^{train}$: lead time in weeks from port *k* to DC *j* given that items are transported by train.
LT_{k}^{ship} : lead time in weeks from China to port k given that items are transported by ship

The total holding costs consists of the pipeline stock downstream and upstream of the DC, the costs depends on whether the transportation is done by truck or train.

Pipeline stock downstream DC:

$$\sum_j \sum_i [\, LT_{j,i}^{truck} * D_i * x_{j,i}^{truck} + LT_{j,i}^{train} * D_i * x_{j,i}^{train}]h \tag{15}$$

Pipeline stock upstream DC:

$$\sum_j \sum_k [(Q_{k,j}^{truck} * (\, LT_{k,j}^{truck} + LT_k^{ship}\,)) + (Q_{k,j}^{train} * (\, LT_{k,j}^{train} + LT_k^{ship}\,))]h \tag{16}$$

The SS is hold at the DC:

$$SS_{k,j}^{truck} = 1.645 * D_{i(per\ week)} \sqrt{LT_{k,j}^{truck} + LT_k^{ship}}$$

$$SS_{k,j}^{train} = 1.645 * D_{i(per\ week)} \sqrt{LT_{k,j}^{train} + LT_k^{ship}} \tag{17}$$

To calculate the total holding cost, the SS has to added to the $Q_{k,j}$, the amount of containers which are transported to DC_j. The lead time is in weeks, the minimization will be also for a week. This means that new parameters has to be add for the container demand per week D_{week} This resulted in the following objective function including the objective function of model 2.

$$\begin{aligned} \min SS_{DC} &= \\ min_{truck,train} &+ \sum_j \sum_i [\, LT_{j,i}^{truck} * Dweek_i * x_{j,i}^{truck} + LT_{j,i}^{train} * Dweek_i * x_{j,i}^{train}]h \\ &+ \sum_j \sum_k [(Q_{k,j}^{truck} * (\, LT_{k,j}^{truck} + LT_k^{ship} + SS_{k,j}^{truck}) + Q_{k,j}^{train} \\ &* ((\, LT_{k,j}^{train} + LT_k^{ship}\,) + SS_{k,j}^{train}))]h \end{aligned} \tag{18}$$

5.4.1 Results

Including inventories gives a slightly different result than the models so far. The optimal solution of this supply chain design includes just one port and one DC, Rotterdam and Venlo. All the transportation of the containers from port to DC is done per truck, since Venlo is less than 200km located from Rotterdam. From Venlo twice the transportation occurs per truck, this is to Eindhoven and Frankfurt. Remaining transport connections are served by train. Remarkable is that Frankfurt is more than 200 km located from Venlo, this implies according to (3) that the transportation should occur by train. In this model, inventories are taken into account as well. The pipeline stock is dependent on the lead time of the goods. The lead time per train is larger than per truck, therefore is could be more beneficial to use the truck instead of the train. The holding cost will be reduced if the truck is used. The costs of the supply chain can be found in table 5.4.1 and an overview of which DR is served by truck and which by train is given in **appendix G.**

Table 5.4.1 Costs and percentage of model 4

Costs of	Costs	Percentage
Transport DC-DR	€ 8,029,382.40	0.28%
Transport Port - DC	€ 139,922,344.00	4.87%
Opening DC	€ 789,971.12	0.03%
Port	€ 1,147,037,820.00	39.92%
Holding cost	€ 1,577,527,007.28	54.90%
Total cost	**€ 2,873,306,524.80**	

The costs for one week are €2,873,306,524.80, this means that for one year the costs are 52* €2,873,306,524.80 = € 149,411,939,289.55

5.4.2 Conclusion

In the optimal supply chain where costs are minimized there is only one port and one DC opened. The fact that there is just one DC opened is due to the high holding costs. The lead time from China to the DC is more than a month. For this time period there must be a SS. If at every DC a SS stock has to be stored for over a month, the cost will be very high. Therefore, the only DC which is opened is Venlo.

It could be seen from tables 4.1 that about a half of the costs are caused by the holding costs. Due to the holding costs Frankfurt is served by truck instead of a train. In model 2, Frankfurt is served from Venlo as well, but in that case it occurs by train. This is in line with the equation (3)

5.5 Model 5

In this model the costs of CO2 - emissions are included. There are many approaches to take the CO2-emissions into account. The costs of emission are incorporated in three different ways. First the objective function is only minimized on the transport costs. This is the same as minimizing model 2... Secondly the objective function is minimized on emission costs. However, in both cases one part of the objective function is minimized. The other part of the costs, emissions and transport respectively, has to be calculated by using the results of the design of the supply chain obtained from the other part. This means if transport costs are minimized, this result is used to calculate the costs of emissions and the other way around. Finally, both costs emission and transport costs are minimized.

To implement to emissions in the model a few new parameters have to be added:

WD_i : Cargo weight of demand in region *i* (t/year).
LC : Weight of load in container (t/container)
E^{train} : CO_2 emissions from train transportation (tCO2 /km/t).
E^{truck} : CO_2 emissions from train transportation (tCO2 /km/t).
E^{ship} : CO_2 emissions from maritime transport (tCO2/km/t)
P_{CO_2} : Unit price CO_2 emissions (€/tCO2).
d_{kj} : distance from port *k* to DC *j* (km).

d_{ji} : distance from DC j to demand region I (km).
d_k : distance from Shanghai to port k (km).

All constraints remain the same, only the objective function is adjusted by adding to $\min SS_{DC}$ the following function.

$$P_{C02}\Bigg[\sum_i\sum_j WD_i\left(d_{j,i}x_{j,i}^{truck}E^{truck} + d_{j,i}x_{j,i}^{train}E^{train}\right) + \sum_k\sum_j\Big[\left(d_{k,j}Q_{k,j}^{truck}E^{truck} + d_{k,j}Q_{k,j}^{train}E^{train}\right) + \left(\left(d_kE^{ship}\left(Q_{k,j}^{truck} + Q_{k,j}^{train}\right)\right)\right]LC\Bigg] \quad (19)$$

5.5.1 Results

5.5.1.1 Minimization on emission:

In **appendix H** shows the result of the supply chain which minimizes cost is. Remarkable is that all transportation occurs per train and just one port and DC is used, Bucharest. Table 5.5.1.1a show the emission costs for the shipment from Shanghai to Constanta, for the transportation from Constanta to Bucharest and transportation from Bucharest to the DRs. Remarkable is the huge costs for the shipment. The high costs explain the use of one port, one of the nearest ports to Shanghai and that is Constanta. Table 5.5.1.1b shows that, apart from Bucharest, all DCs are far located from Constanta. Therefore, the only DC which is opened is Bucharest. Bucharest serves all DRs.

Table 5.5.1.1a: Emission Costs Model 5.5.1.1

Emission costs of	Costs	Percentage
Shanghai - Constanta	€ 24,196,016.50	25.2%
Constanta - Bucharest	€4,780,340.41	5.0%
Bucharest - DRs	€ 67,012,638.07	69.8%
Total	€ 95,988,994.98	

Table 5.5.1.1b

Haven/DC	Venlo	Parijs	Frankfurt	Berlin	Prague	Warsaw	Budapest	Bucharest
Constanta(port)	2279	2525	2003	1908	1564	1586	1046	227

From table 5.1.1.1a is could be seen that most costs are caused by emission costs from transporting the refrigerators to all DRs. The DC Bucharest is far located from some DRs. The emission is dependent of distance and this resulted in the high emission costs.

Since the minimization occurs on the emission costs, the transportation and holding costs are calculated manually using the results of the minimization. Transportation costs can be divided in the six terms of (18).

1. Cost of using Constanta: variable costs for using this port are €3540/container. Total costs are 406751 containers * 3540 = €1439898540, - .
2. Transportation costs from Constanta to Bucharest by train: Variable costs are €1/km/container and €200/container. This results in 17537*406751*1+406751*200=€7214542487,-.
3. Transportation costs from Bucharest to all DRs: All transportation occurs per train. The calculation can be found in **appendix I**. The total costs for the transportation of all containers from Bucharest to the different DR are €838265725.
4. Cost of opening the distribution centre in Bucharest: variable cost of opening are €0,267/container/day and fixed cost are €4250, 5/day. This results in (0,267*406751+4250,5)*365 = €41191351,21,-.
5. Holding costs: because the transportation occurs only per train the holding cost are: $\sum_j \sum_i [(LT_{j,i}^{train} * D_i + SS_{j,i}^{train}) * x_{j,i}^{train}]h + \sum_j \sum_k (Q_{k,j}^{train} * (LT_{k,j}^{train} + LT_k^{ship}))h$. The costs of the first term €389600663.
6. The last term can be easily computed: 406751 containers*(0,14+30/7)*0.1*150*56=€1512137518. The total costs are €1901738181.

An overview of all the terms is stated in table 5.5.1.1c.

Table 5.5.1.1c: Transport Costs using emission minimization

Cost of	Costs
Port	€ 1.439.898.540,00
Transport Port - DC	€ 7.214.542.487,00
Opening DC	€ 41.191.351,00
Transport DC-DR	€ 838.265.725,00
Holding cost	€ 1.901.738.181,00
Total	€ 11.435.636.284,00

Minimization of the emission costs leads to a total cost of € 95,988,994.98+ € 11.435.636.284, 00 = €11,531,625,278.98

5.5.1.2 Minimization of transport cost

The result of this minimization can be found in the previous results of model 5.4. The total costs for that model were €2,873,306,524.80 per week. Using these results the cost of emission can be computed. These emissions costs consist of:

1. costs for the shipment from Shanghai to Rotterdam
   $P_{CO2} \sum_k \sum_j \left(d_k E^{ship} (Q_{k,j}^{truck} + Q_{k,j}^{train}) \right) * LC$ =
   40*22222*0.000019*406761*56*79.7/1000 = €30,659,969.00

2. costs for the transportation from Rotterdam to Venlo
   $P_{CO2} \sum_k \sum_j (d_{k,j} Q_{k,j}^{truck} E^{truck} + d_{k,j} Q_{k,j}^{train} E^{train}) * LC$=
   40*172*406751*0.000062*56*79.7/1000 = €774.381.74

3. costs for transportation from Venlo to the DRs.

$P_{C02} \sum_i \sum_j WD_i \left(d_{j,i} x_{j,i}^{truck} E^{truck} + d_{j,i} x_{j,i}^{train} E^{train}\right)$, this calculation is very complicated to do manually because we have to calculate the emission to very DR. For the first two terms there was only one port of DC for which the emission costs must be calculated. A part of the calculation can be found in **appendix J** €24,658,596.67 per week.
An overview of the three terms is stated in table 5.5.1.2, this table also includes the total costs.

Table 5.5.1.1a: Emission Costs Model 5.5.1.2

Emission costs of	Costs	Percentage
Shanghai - Constanta	€30,659,969.00	54.7%
Constanta - Bucharest	€774,381.74	1.4%
Bucharest - DRs	€ 24,658,596.67	44.0%
Total	€ 56,092,947.41	

The total costs for this model are € 56,092,947.41+€2,873,306,524.80= € 2,929,399,472.21.

5.5.1.3 Minimization on both emission and transport costs (SS stored at DR)

Optimization on both emission and transport costs gives exactly the same if we compare the supply chain network to model 5.4, only the costs will increase due to the emission costs. The costs for emission can be computed in the way as we did for model 5.5.1.2. The total costs of emission are now €31,469,088.93, adding this costs to the total costs of model 5.4, lead to the total costs of €2,873,306,524.80 + €31,469,088.93 = € 2,904,775,613.73.

5.5.2 Conclusion

Model	5.5.1	5.5.2	5.5.3
Transport Costs	€ 95,988,994.98	€2,873,306,524.80	€2,873,306,524.80
Emission Costs	€ 11.435.636.284, 00	€ 56,092,947.41	€31,469,088.93
Total Costs	€11,531,625,278.98	€ 2,929,399,472.21	€ 2,904,775,613.73

6 Conclusions

	Model 1	Model 2	Model 3	Model 4.1	Model 4.2	Model 5.1	Model 5.2	Model 5.3
Ports								
Rotterdam	X	X	X	X	X		X	X
Lisbon								
Trieste	X	X	X		X			
Hamburg	X	X	X		X			
Marseille								
La Havre								
Constanta	X	X	X		X	X		
DC								
Venlo	X	X	X	X	X		X	X
Parijs	X	X	X		X			
Frankfurt		X	X		X			
Berlin	X	X	X		X			
Praque		X	X		X			
Warsaw		X	X		X			
Budapest	X	X	X		X			
Bucharest	X	X	X		X	X		
Total Costs								

7 Further Research

NOTE: I find on Friday the 6th of June an enormous fault in the data I implemented in AIMMS. This was mainly due to analysing results. I used wrong distances between Bucharest and Budapest. The distance between Bucharest and Budapest is now set as 15, which was assumed to be the distance between the distribution centre of Bucharest and the demand region of Bucharest. Since almost all parameters are dependent on distance I have to recalculate the whole model. Because I have to submit is in almost 2 hours I am not be able to rewrite all results. I will do this the coming days. The models remain the same.

Furthermore, the safety stock is assumed to be at one place. It could be that the SS is stored at the DC and DR. This is not incorporated in the model. It could be analysed how much the costs will increase if at both DC and DR the SS is located. This reduces the uncertainty and increased the customers service because the change that goods are out of stock will be limited

Due to misinterpreted and different available data, I took other average speed for the train. I have to recalculate the lead time for train and run the model again in AIMMS.

Due to time limits I did not perform a sensitivity analysis on the last two models. I will do this in the next week and incorporating this in the final model.

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9 Appendices

Appendix A: Clear overview of the three sets

Ports
Rotterdam
Lisbon
Trieste
Hamburg
Marseille
La Havre
Constanta(port)

Distribution Centres (DCs)
Venlo
Parijs
Frankfurt
Berlin
Praque
Warsaw
Budapest
Bucharest

Demand Regions (DRs)
Eindhoven
Sofia
Prague
Copenhagen
Munich
Berlin
Hamburg
Frankfurt
Riga
Athens
Madrid
Toulouse
Paris
Rome
Budapest
Vienna
Warsaw
Bucharest
Ljubljana
Helsinki
Stockholm
London

Appendix B: Clear overview of the parameters

In the enclosed excel file: Data per variable all parameters are defined clearly.

Appendix C: Results model 1

Tabel 1: Transportation mode between port and DC

Port/DC	Venlo	Paris	Frankfurt	Berlin	Prague	Warsaw	Budapest	Bucharest
Rotterdam	Truck	Truck	x	x	x	x	x	x
Lisbon	x	x	x	x	x	x	x	x
Trieste	x	x	x	x	x	x	Truck	x
Hamburg	x	x	x	Truck	x	x	x	x
Marseille	x	x	x	x	x	x	x	x
La Havre	x	x	x	x	x	x	x	x
Constanta(port)	x	x	x	x	x	x	x	Truck

Tabel 2: Transportation mode between DC and DR

DR/DC	Venlo	Paris	Frankfurt	Berlin	Prague	Warsaw	Boedapest	Bucharest
Eindhoven	Truck	x	x	x	x	x	x	X
Sofia	x	x	x	x	x	x	x	Truck
Praag	x	x	x	Truck	x	x	x	x
Copenhagen	x	x	x	Truck	x	x	x	x
Munich	Truck	x	x	x	x	x	x	x
Berlin	x	x	x	Truck	x	x	x	x
Hamburg	Truck	x	x		x	x	x	x
Frankfurt	Truck	x	x		x	x	x	x
Riga	x	x	x	Truck	x	x	x	x
Athens	x	x	x	x	x	x	x	Truck
Madrid	x	Truck	x	x	x	x	x	x
Toulouse	x	Truck	x	x	x	x	x	x
Paris	x	Truck	x	x	x	x	x	x
Rome	Truck	x	x	x	x	x	x	x
Boedapest	x	x	x	x	x	x	Truck	x
Vienna	x	x	x	Truck	x	x	x	x
Warsaw	x	x	x	Truck	x	x	x	x
Bucharest	x	x	x	x	x	x	x	Truck
Ljubljana	Truck	x	x	x	x	x	x	x
Helsinki	x	x	x	Truck	x	x	x	x
Stockholm	x	x	x	Truck	x	x	x	x
London	Truck	x	x	x	x	x	x	x

Appendix D: Model 2

$$
\begin{aligned}
min_{truck,train} \;=\; & min \sum_{j\in J}\Bigg(\sum_{i\in I} D_i\big(c_{ji}^{truck} + A_{truck}\big)x_{ji}^{truck} \\
& + \sum_{i\in I} D_i\big(c_{ji}^{train} + A_{train}\big)\, x_{ji}^{train}\Bigg) \\
& + \sum_{k\in K}\sum_{j\in J}[Q_{kj}^{train}(c_{kj}^{train} + A^{train}) + \; Q_{k\,j}^{\;truck}(c_{kj}^{truck} + \; A_{truck})] \\
& + \sum_{j\in J} y_j\, FC_j + \sum_{j\in J} VC_j \sum_{k\in K}\big(Q_{kj}^{train} + \; Q_{kj}^{truck}\big) \\
& + \sum_{k\in K} PC_k \sum_{j\in J}\big(Q_{kj}^{train} + \; Q_{kj}^{truck}\big)\;,
\end{aligned}
$$

$s.t.$

$$
\sum_{j\in J}(x_{ji}^{train} + \; x_{ji}^{truck}) = 1\,, \qquad \forall\; i \in I,
$$

$$\sum_{i \in I} (x_{ji}^{train-} + x_{ji}^{truck}) D_i \leq \sum_{k \in K} (Q_{kj}^{train} + Q_{kj}^{truck}), \qquad \forall j \in J,$$

$$\sum_{k \in K} Q_{kj}^{truck} + Q_{kj}^{train} \leq y_j * M, \qquad \forall j \in J,.$$

$$x_{ij} \in \{1,0\}, y_j \in \{1,0\}, Q_{kj} \geq 0, \qquad \forall i \in I, j \in J, k \in K.$$

Appendix E: Results model 2

Tabel 3: Transportation mode between port and DC

Port/DC	Venlo	Paris	Frankfurt	Berlin	Prague	Warsaw	Budapest	Bucharest
Rotterdam	Truck	Train	Train	x	x	x	x	x
Lisbon	x	x	x	x	x	x	x	x
Trieste	x	x	x	x	x	x	Train	x
Hamburg	x	x	x	Train	Train	Train	x	x
Marseille	x	x	x	x	x	x	x	x
La Havre	x	x	x	x	x	x	x	x
Constanta(port)	x	x	x	x	x	x	x	Train

Tabel 4: Transportation mode between DC and DR

DR/DC	Venlo	Paris	Frankfurt	Berlin	Prague	Warsaw	Boedapest	Bucharest
Eindhoven	Truck	x	x	x	x	x	x	x
Sofia	x	x	x	x	x	x	x	Train
Praag	x	x	x	x	Truck	x	x	x
Copenhagen	x	x	x	Train	x	x	x	x
Munich	Train	x	x	x	x	x	x	x
Berlin	x	x	x	Truck	x	x	x	x
Hamburg	Train	x	x	x	x	x	x	x
Frankfurt	x	x	Truck	x	x	x	x	x
Riga	x	x	x	x	x	Train	x	x
Athens	x	x	x	x	x	x	x	Train
Madrid	x	x	Train	x	x	x	x	x
Toulouse	x	x	Train	x	x	x	x	x
Paris	x	Truck	x	x	x	x	x	x
Rome	Train	x	x	x	x	x	x	x
Boedapest	x	x	x	x	x	x	Truck	x
Vienna	x	x	x	Train	x	x	x	x
Warsaw	x	x	x	x	x	Truck	x	x
Bucharest	x	x	x	x	x	x	x	Truck
Ljubljana	Train	x	x	x	x	x	x	x
Helsinki	x	x	x	x	x	Train	x	x
Stockholm	x	x	x	Train	x	x	x	x
London	Train	x	x	x	x	x	x	x

Appendix F: Model 3

Model

$$min_{train,train,barge} = \min \sum_{j\in J}\left(\sum_{i\in I} D_i\left(c_{ji}^{truck} + A_{truck}\right)x_{ji}^{truck} + \sum_{i\in I} D_i\left(c_{ji}^{train} + A_{train}\right)x_{ji}^{train} + \sum_{i\in I} D_i\left(c_{ji}^{barge} + A_{barge}\right)x_{ji}^{barge}\right)$$
$$+ \sum_{k\in K}\sum_{j\in J}[Q_{kj}^{train}(c_{kj}^{train} + A^{train}) + Q_{k\,j}^{truck}(c_{kj}^{truck} + A_{truck}$$
$$+ Q_{k\,j}^{barge}(c_{kj}^{barge} + A_{barge})] + \sum_{j\in J} y_j\, FC_j$$
$$+ \sum_{j\in J} VC_j \sum_{k\in K}\left(Q_{kj}^{train} + Q_{kj}^{truck} + Q_{kj}^{barge}\right)$$
$$+ \sum_{k\in K} PC_k \sum_{j\in J}\left(Q_{kj}^{train} + Q_{kj}^{truck} + Q_{kj}^{barge}\right),$$

$s.t.$

$$\sum_{j\in J}(x_{ji}^{train} + x_{ji}^{truck} + x_{ji}^{barge}) = 1, \qquad \forall\, i \in I,$$

$$\sum_{i\in I}(x_{ji}^{train} + x_{ji}^{truck} + x_{ji}^{barge})D_i \le \sum_{k\in K}(Q_{kj}^{train} + Q_{kj}^{truck} + Q_{kj}^{barge}), \qquad \forall\, j \in J,$$

$$\sum_{k\in K} Q_{kj}^{truck} + Q_{kj}^{train} + Q_{kj}^{barge} \le y_j * M, \qquad \forall j \in J,.$$

$$x_{ij} \in \{1{,}0\}, y_j \in \{1{,}0\}, Q_{kj} \ge 0, \qquad \forall i \in I, j \in J, k \in K.$$

Appendix G: Results model 5.4

DR/DC	Venlo	Paris	Frankfurt	Berlin	Prague	Warsaw	Boedapest	Bucharest
Eindhoven	Truck	x	x	x	x	x	x	X
Sofia	Train	x	x	x	x	x	x	x
Praag	Train	x	x	x	x	x	x	x
Copenhagen	Train	x	x	x	x	x	x	x
Munich	Train	x	x	x	x	x	x	x
Berlin	Train	x	x	x	x	x	x	x
Hamburg	Train	x	x	x	x	x	x	x
Frankfurt	Truck	x	x	x	x	x	x	x
Riga	Train	x	x	x	x	x	x	x
Athens	Train	x	x	x	x	x	x	x

Madrid	Train	x	x	x	x	x	x	x
Toulouse	Train	x	x	x	x	x	x	x
Paris	Train	x	x	x	x	x	x	x
Rome	Train	x	x	x	x	x	x	x
Boedapest	Train	x	x	x	x	x	x	x
Vienna	Train	x	x	x	x	x	x	x
Warsaw	Train	x	x	x	x	x	x	x
Bucharest	Train	x	x	x	x	x	x	x
Ljubljana	Train	x	x	x	x	x	x	x
Helsinki	Train	x	x	x	x	x	x	x
Stockholm	Train	x	x	x	x	x	x	x
London	Train	x	x	x	x	x	x	x

Appendix H: Results Model 5.5.1.1

Port/DC	Venlo	Paris	Frankfurt	Berlin	Prague	Warsaw	Budapest	Bucharest
Rotterdam	x	x	x	x	x	x	x	x
Lisbon	x	x	x	x	x	x	x	x
Trieste	x	x	x	x	x	x	x	x
Hamburg	x	x	x	x	x	x	x	x
Marseille	x	x	x	x	x	x	x	x
La Havre	x	x	x	x	x	x	x	x
Constanta(port)	x	x	x	x	x	x	x	Train

i	Venlo	Parijs	Frankfurt	Berlijn	Praag	Warsaw	Buapest	Bucharest
Eindhoven	x	x	x	x	x	x	x	Train
Sofia	x	x	x	x	x	x	x	Train
Praag	x	x	x	x	x	x	x	Train
Kopenhagen	x	x	x	x	x	x	x	Train
Munchen	x	x	x	x	x	x	x	Train
Berlin	x	x	x	x	x	x	x	Train
Hamburg	x	x	x	x	x	x	x	Train
Frankfurt	x	x	x	x	x	x	x	Train
Riga	x	x	x	x	x	x	x	Train
Athene	x	x	x	x	x	x	x	Train
Madrid	x	x	x	x	x	x	x	Train
Toulouse	x	x	x	x	x	x	x	Train
Paris	x	x	x	x	x	x	x	Train
Rome	x	x	x	x	x	x	x	Train
Budapest	x	x	x	x	x	x	x	Train

Wenen	x	x	x	x	x	x	x	Train
Warsaw	x	x	x	x	x	x	x	Train
Bucharest	x	x	x	x	x	x	x	Train
Ljubjana	x	x	x	x	x	x	x	Train
Helsinki	x	x	x	x	x	x	x	Train
Stockholm	x	x	x	x	x	x	x	Train
London	x	x	x	x	x	x	x	Train

Appendix I: Calculation Transportation Costs from Bucharest to all DR for Model 5.5.1.1

Demand Region	Eindhoven	Sofia	Prague	Copenhagen	Munich	Berlin	Hamburg	Frankfurt	Riga	Athens	Madrid	Toulouse	Paris	Rome	Budapest	Vienna	Warsaw	Bucharest	Ljubljana	Helsinki	Stockholm	London
Bucharest, variable cost/container	2108	349	1339	2122	1498	1682	1979	1778	1973	1219	3332	2575	2299	2038	821	1057	1356	15	1273	2369	2767	1575
Bucharest, fixed cost/container	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Container Demand Region	26798	3233	12038	4799	22682	15820	12821	28073	3232	4588	19313	23711	39343	26597	6580	11297	24762	6631	2600	5089	17268	89476
Total costs per Demand Region(€)	61849784	1774917	18526482	11143278	38514036	29773240	27936959	55528394	7023136	6510372	68213516	65798025	98318157	59524086	6718180	14200329	38529672	1425665	3829800	13073641	51234156	158819900
Total costs(€)	**838265725**																					

Appendix J: Calculation Emission costs Model 5.5.1.2

Demand Region	Eindhoven	Sofia	Prague	Copenhagen	Munich	Berlin	Hamburg	Frankfurt	Riga	Athens	Madrid	Toulouse	Paris	Rome	Budapest	Vienna	Warsaw	Bucharest	Ljubljana	Helsinki	Stockholm	London
Distance from Venlo	57.3	2002	785	745	668	597	419	284	1785	2718	1731	1143	467	1484	1240	991	1126	2052	1077	1867	1389	507
Emission truck/train	0.000062	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000062	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029	0.000029

Container Demand Region	26798	3233	12038	4799	22682	15820	12821	28073	3232	4588	19313	23711	39343	26597	6580	11297	24762	6631	2600	5089	17268	89476
WC	2300092.954	277490.8769	1033230.8	411901.8615	1946813.508	1357842.769	1100436.292	2409527.185	277405.0462	393791.5692	1657649.646	2035133.369	3376839.954	2282840.969	564766.4615	969630.2	2125341.508	569143.8308	223160	436792.7846	1482125.723	7679793.908
Total costs per Demand Region(€)	218974771.5	52085457.72	283151806.9	42706971.51	855421491.8	371901810.1	171434737.2	1191051898	46411107	142408946.5	1607080204	1599510053	1799255459	2613004816	133633232.9	314804487.6	1718505125	224582760.1	18121886.33	120351143.9	1030925610	10103272895
Total costs(€)	**€24,658,596,671.87**																					