MODELLING OF INTERMODAL NETWORKS

Karl Etlinger[a], Edith Schindlbacher[b], Manfred Gronalt[c]

[a,b,c]Institute of Production and Logistics, University of Natural Resources and Life Sciences, Vienna
Feistmantelstraße 4, 1180 Vienna, Austria

[a]karl.etlinger@boku.ac.at, [b]edith.schindlbacher@boku.ac.at, [c]manfred.gronalt@boku.ac.at

ABSTRACT

This work presents an approach to support intermodal network planning and evaluation by providing a framework of methods for terminal location planning and operational network design. Therefore a mixed integer linear programming model is introduced to optimize the network structure and determine the locations for operating intermodal terminals as well as the type of terminal to be established.
This optimization approach is supposed to be combined with simulation techniques in order to provide a comprehensive planning and evaluation approach for intermodal transportation networks.
Within our work the developed methods and models are also implemented for a case study with test data based on major European transport corridors and future priority axes for freight transportation in Central and Eastern European (CEE) countries.

Keywords: intermodal transportation network, transportation corridor, hub location planning, network optimization

1. INTRODUCTION

Various studies come to the conclusion that the volumes of container traffic will continue to rise steadily after the short stagnation in 2009 caused by the economic crises (Seidelmann 2010). Therefore it is not only inevitable that the expansion of transportation infrastructure continues, but also that the infrastructure in new regions, especially in the CEE countries, is further developed and better connected to main European transport routes. Hence initiatives like RailNetEurope (RNE) and Ten-T (Trans-European Networks) for the development of transportation infrastructure have been launched. RNE is an association of European rail infrastructure managers and allocation bodies that aims at harmonizing conditions and procedures in the field of international rail infrastructure management. The focus of Trans-European Networks, a program of the European Commission, is the further development and expansion of the trans-European transportation corridors. Figure 1 depicts the growth of transportation volumes comparing the actual volumes of 2007 and the volumes forecasted for 2020 in twenty-foot equivalent units (TEU) (UIC 2010).

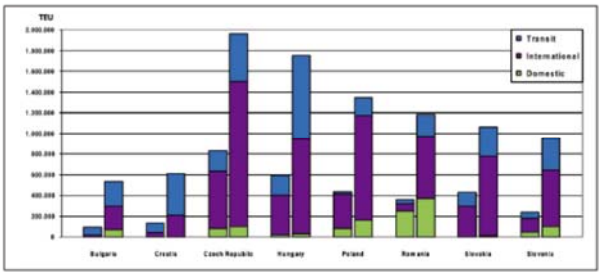

Figure 1: Comparison Of Transportation Volumes 2007 And 2020 (UIC 2010)

As a consequence of this development the experts of the International Union of Railways (UIC) expect the emergence of substantial bottlenecks in the rail infrastructure as well as terminal capacities by 2015 (Seidelmann 2010).

The emerging challenge is the timely planning of the expansion of transportation infrastructure and the introduction of efficient operational concepts for terminals as well as railways in intermodal transport (European Commission 2005).

When developing a method framework for the planning and evaluation of intermodal transport networks one faces a twofold problem. On the one hand there are long term decisions at a strategic level to be made but on the other hand, at the same time one has to deal with short term decisions at a tactical and operational level.

At the strategic level, decisions are found on a very long term, typically 10 to 20 years. This includes the location of terminals, network configurations and the design and layout of the terminals. Typically these are decisions where a large amount of capital is fixed for a long time and which are difficult to change retroactively (Macharis and Bontekoning 2004).

In general, when dealing with hub location problems, the concern is how to locate hub facilities and allocate demand nodes to these hubs in order to route the occurring traffic from an origin to a destination node within the network. Since optimal allocations are affected by hub locations and vice versa it is important not to deal with these two problems separately, as sometimes did in literature, but consider them together in the process of designing a hub network (Alumur and Kara 2008).

Macharis and Bontekoning (2004) state that operational research (OR) has focused mostly on uni-modal transport problems and that intermodal freight transport is only just starting to be researched seriously. Since intermodal transport systems are more complex compared to mono-modal ones, there is a need for the development of different OR techniques for intermodal freight transport research.

Caris et al. (2013) give an overview of new research themes in different areas concerning the development of decision support systems in intermodal transport.

At the tactical level the network operator has to determine which services will be offered and hence the corresponding service schedules have to be fixed. Secondly he has to decide which production model should be used i.e. how to operate the trains. This includes decisions like frequency of service, train length etc. (Macharis and Bontekoning 2004).

Even when focusing only on the tactical and operational levels, due to the complexity of intermodal transportation systems, a majority of the work in this field only deals with a certain aspect of the system and specific problem statements. So there are particular models for the calculation of the modal split based on costs for rail- and road traffic (Floden 2007) or models for the detailed simulation of the processes taking place at intermodal terminals as well as simulation models of those terminals (Gronalt et al. 2012). Rizzoli et al. (2002) and Gambardella et al. (2002) combine an agent based simulation model and a discrete event simulation for planning the flow of loading units between inland container terminals. Schindlbacher and Gronalt (2010) present an approach for the use of auction mechanisms to coordinate container flows in intermodal freight transportation networks whereas Bierwirth et al. (2012) focus on the transport service selection in intermodal rail/road distribution networks.

The authors propose a method framework for the planning and evaluation of intermodal rail/road transportation networks in order to support the decision processes necessitated by the aforementioned future development of transportation infrastructure. The goal is to provide an integrated approach that considers the strategic as well as the tactical and operational planning levels in one comprehensive approach that allows for interdependencies of the different planning perspectives.

2. MATERIAL AND METHODS

To track the problem at hand, we use two different methods to deal with the complexity of intermodal transportation networks.

For the long term planning of the intermodal network design at the strategic level, which is the main focus of this work, we develop an optimization model for the terminal location planning problem in order to create the basic network topology.

At the tactical and operational levels we approach the short term planning by developing a multi-agent simulation model which builds on the results of the terminal location optimization.

To design our transportation network we start by dividing the analyzed geographical area into smaller regions. Those regions are the origin and destination regions for the intermodal loading units in our model. We then identify a number of potential hub locations in the considered geographical area. Depending on the aim of the analysis the selection of those potential hub locations can be influenced by existing infrastructure, population density, regional economic power, geographic structure etc.

For real data analysis the granularity of the origin and destination regions is mainly determined by the availability of the required data on freight transportation volumes. Since it makes no sense to subdivide into areas for which there is no data available, the granularity of the regions is determined by the level of detail of the available data.

We now build a transportation network consisting of terminals and rail links connecting the terminals within the geographical area.

This is the basis for the routing of freight traffic in the network at the aggregated strategic level. At this level only aggregated transportation volumes such as yearly data are considered.

The disaggregation follows in the detailed planning of single train connections and terminal services at the tactical and operational levels.

2.1. Hub location planning

To solve the hub location planning problem, we modify and extend the well-known single allocation hub location problem (see Alumur and Kara (2008) for an overview of hub location problems) as presented in Alumur et al. (2009) and formulate a mixed integer linear programming model to approach our task at hand.

The optimization model creates the basic topology of the analyzed transportation network. The network consists of a set of nodes as well as arcs connecting the nodes in the network. The nodes can be divided into supply/demand nodes and hub-nodes. Supply/demand nodes represent the origin and destination regions of the analyzed transportation network and therefore are the starting- and endpoints for the flows of loading units in the network. They will be denoted as non-hub nodes subsequently. In our model we consider different types of hub nodes as introduced by Clausen and Sender (2011). These nodes represent different types of terminals, like gateway and feeder terminals which differ in their capacity, fixed operating costs as well as transshipment costs. They can also be distinguished by the number of connecting links they can have with the network.

The decision at which nodes a terminal should be established and what type of terminal it should be is based on the estimated volume of loading units that have to be handled by the network and the costs of transportation services as well as terminal operations.

The model chooses nodes out of a given pool of potential hub location nodes and determines the type of terminal that should be placed at those nodes in order to minimize the overall network costs while ensuring that all traffic can be handled and is transported from its origin to the assigned destination.

In the model formulation we emphasize model flexibility and the possibility to quickly adapt the model to a variety of problems, even though this means an increased level of complexity. Therefore, we relax the assumption that the hub network is a complete network with a link between every pair of hubs, as it is made in many other works in the area of hub location problems (Alumur and Kara 2008), and allow for complete as well as incomplete network structures in our model solutions.

The model also can be quickly adopted for either capacitated or uncapacitated problem statements as well as the inclusion or exclusion of fixed costs.

2.1.1. Mathematical model

For the mathematical formulation of our hub location problem we define a graph $G = (N, A)$ where N is the set of nodes and A the set of arcs of the graph. Let H be the set of potential hub locations such that $H \subseteq N$ with h hubs. Arcs that connect two hubs will be referred to as hub-links hereafter.

In order to present the mathematical formulation we define the following parameters:

p	number of hubs to be established
q	number of hub-links with $q \in \left\{p-1, \dots, \frac{(p-1)p}{2}\right\}$
c_{ij}	distance between nodes $i \in N$ and $j \in N$
c_{ij}^{truck}	transportation costs for one unit of flow between nodes $i \in N$ and $j \in N$ when carried by truck
c_{ij}^{train}	transportation costs for one unit of flow between nodes $i \in N$ and $j \in N$ when carried by train
w_{ij}	given flow from node $i \in N$ to node $j \in N$
O_i	total flow originating at node $i \in N$
D_j	total flow bound for node $j \in N$
$\bar{\Gamma}_k^c$	capacity of a hub of type $c \in L$ at node $k \in H$ where $L = \{1, \dots, c\}$ is the set of hub types
Θ_{kl}	capacity of a hub-link connecting hubs $k \in H$ and hub $l \in H$
F_{kl}	minimum flow required to establish a hub-link between hub $k \in H$ and hub $l \in H$
a^c	maximum number of hub-links that can be connected to a hub of type $c \in L$
$\overline{Ch}_k^c$	cost for a hub of type $c \in L$ at node $k \in H$
Cl_{kl}	cost of installing a hub-link between hubs $k \in H$ and $l \in H$
$\overline{cch}_k^c$	cost for cargo handling at hub $k \in H$ with capacity level $c \in L$

Decision variables:

$$x_{ik} = \begin{cases} 1, & \text{if node } i \in N \text{ is allocated to hub } k \in H \\ 0, & \text{otherwise} \end{cases}$$

$$y_{kl} = \begin{cases} 1, & \text{if a link is established between } k \in H \text{ and } l \in H \\ 0, & \text{otherwise} \end{cases}$$

f_{kl}^i flow from node $i \in N$ to hub $l \in H$ via hub $k \in H$

$$g_k^c = \begin{cases} 1, & \text{if node } k \in H \text{ is a hub of hub type } c \in L \\ 0, & \text{otherwise} \end{cases}$$

The model formulation is given as follows:

$$\min \sum_{i \in N} \sum_{\substack{k \in H: \\ k \neq i}} c_{ik}^{truck} O_i x_{ik} + \sum_{i \in N} \sum_{\substack{k \in H: \\ k \neq i}} c_{ki}^{truck} D_i x_{ik} \tag{1a}$$

$$+ \sum_{k \in H} \sum_{l \in H} \sum_{i \in N} c_{kl}^{train} f_{kl}^i \tag{1b}$$

$$+ \sum_{k \in H} \sum_{c \in L} \overline{Ch}_k^c \, g_k^c \tag{1c}$$

$$+ \sum_{i \in N} \sum_{k \in H} \sum_{\substack{l \in H: \\ l \neq k}} \sum_{c \in L} f_{lk}^i \overline{cch}_k^c g_k^c + \sum_{i \in N} \sum_{k \in H} \sum_{c \in L} O_i x_{ik} g_k^c \overline{cch}_k^c \tag{1d}$$

$$\sum_{k \in H} \sum_{c \in L} ld1_k^c \overline{cch}_k^c + \sum_{i \in N} \sum_{k \in H} \sum_{c \in L} O_i ld2_{ik}^c \overline{cch}_k^c \tag{1e}$$

subject to:

$$\sum_{k \in H} x_{kk} = p \tag{2}$$

$$\sum_{k \in H} \sum_{l \in H: k < l} y_{kl} = q \tag{3}$$

$$\sum_{k \in H} x_{ik} = 1 \qquad \forall\ i \in N \tag{4}$$

$$x_{ik} \leq x_{kk} \qquad \forall\ i \in N, k \in H \tag{5}$$

$$y_{kl} \leq x_{kk} \qquad \forall\ k, l \in H: k < l \tag{6}$$

$$y_{kl} \leq x_{ll} \qquad \forall\ k, l \in H: k < l \tag{7}$$

$$\sum_{l \in H: l \neq k} f_{lk}^{it} + O_i^t x_{ik} = \sum_{l \in H: l \neq k} f_{kl}^{it} + \sum_{j \in N} w_{ij}^t x_{jk} \qquad \forall\ k \in H, i \in N \tag{8}$$

$$f_{kl}^i + f_{lk}^i \leq O_i y_{kl} \qquad \forall\ k, l \in H: k < l, i \in N \tag{9}$$

$$f_{kl}^i \geq 0 \qquad \forall\ k, l \in H: k \neq l, i \in N \tag{10}$$

$$\sum_{i \in N} f_{kl}^{it} \leq \Theta_{kl} \qquad \forall\ k, l \in H: k \neq l \tag{11}$$

$$\sum_{i \in N} f_{kl}^i \geq F_{kl}(y_{kl} + y_{lk}) \qquad \forall\ k, l \in H: k \neq l \tag{12}$$

$$\sum_{i \in N, k \in H: k \neq l} f_{kl}^i \leq \sum_{i \in N} D_i x_{il} - \sum_{u, z \in N: u \neq z} w_{uz} x_{ul} x_{zl} + \left(\left(\sum_{\substack{m \in H: \\ l < m}} y_{lm} + \sum_{\substack{e \in H: \\ e < k}} y_{el} \right) - 1 \right) n + (x_{ll}(-n) + n) \qquad \forall\ l \in H \tag{13}$$

$$\begin{aligned}&\sum_{i\in N, l\in H: l\neq k} f_{lk}^{i} \le \sum_{i\in N} D_i x_{ik} - \sum_{u,z\in N: u\neq z} w_{uz} ld3_{uzk} \\ &+ \left(\left(\sum_{m\in H: k<m} y_{km} + \sum_{e\in H: e<k} y_{ek}\right) - 1\right) * \sum_{i\in N} D_i \\ &+ \left(x_{kk} * (-1 * \sum_{i\in N} D_i) + \sum_{i\in N} D_i\right) \\ &\qquad \forall\ k \in H\end{aligned} \tag{14}$$

$$\sum_{c\in L} g_k^c = x_{kk} \qquad \forall\ k \in H \tag{15}$$

$$\sum_{i\in N} O_i^t x_{ik} \le \sum_{c\in L} \bar{\Gamma}_k^c g_k^c \qquad \forall\ k \in H \tag{16}$$

$$\sum_{l\in H} (y_{kl} + y_{lk}) \le g_k^c * a + n \sum_{s\in L: s\neq c} g_k^s \qquad \forall\ k \in H, c = m \tag{17}$$

$$0 \le ld1_k^c \le \sum_{i\in N} O_i g_k^c \qquad \forall\ k \in H, c \in L \tag{18}$$

$$0 \le \sum_{i\in N} \sum_{l\in H: l\neq k} \left(f_{lk}^i\right) - ld1_k^c \le \sum_{i\in N} O_i (1 - g_k^c) \qquad \forall\ k \in H, c \in L \tag{19}$$

$$ld2_{ik}^c \le x_{ik} \qquad \forall\ i \in N, k \in H, c \in L \tag{20}$$

$$ld2_{ik}^c \le g_k^c \qquad \forall\ i \in N, k \in H, c \in L \tag{21}$$

$$ld2_{ik}^c \ge x_{ik} + g_k^c - 1 \qquad \forall\ i \in N, k \in H, c \in L \tag{22}$$

$$ld3_{ijk} \le x_{ik} \qquad \forall\ i, j \in N, k \in H \tag{23}$$

$$ld3_{ijk} \le x_{jk} \qquad \forall\ i, j \in N, k \in H \tag{24}$$

$$ld3_{ijk} \ge x_{ik} + x_{jk} - 1 \qquad \forall\ i, j \in N, k \in H: i \neq j \tag{25}$$

$$x_{ik} \in \{0,1\} \qquad \forall\ i \in N, k \in H \tag{26}$$

$$y_{kl} \in \{0,1\} \qquad \forall\ k, l \in H: k < l \tag{27}$$

$$f_{kl}^i \in \mathbb{Z}^+ \qquad \forall\ k, l \in H, i \in N \tag{28}$$

$$g_k^c \in \{0,1\} \qquad \forall\ c \in L, k \in H \tag{29}$$

$$ld1_k^c \in \mathbb{Z}^+ \qquad \forall\ k \in H, c \in L \tag{30}$$

$$ld2_{ik}^c \in \{0,1\} \qquad \forall\ i \in N, k \in H, c \in L \tag{31}$$

$$ld3_{ijk} \in \{0,1\} \qquad \forall\ i, j \in N, k \in H: i \neq j \tag{32}$$

There are three types of flows that form the origin-destination flows within the network. O_i is the collection move respectively the aggregated flow from the origin node i to the first hub. The aggregated flow from the last hub to the destination node j is denoted by D_j. If the flow is routed from one hub to another on a hub-link, this results in a positive f_{kl}^i flow where i is the node of origin and the flow is routed to hub l via hub k (see figure 2).

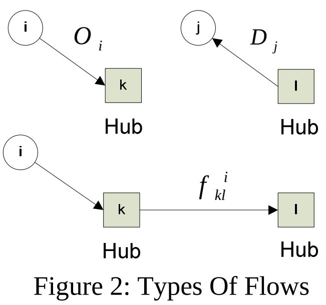

Figure 2: Types Of Flows

Depending on the structure of the network and whether the origin or destination node is a non-hub node or a hub node, an origin-destination flow can be either only one of those flow types or consist of subsequent flows of different types. Please note, that an origin-destination flow can be routed via multiple hubs and therefore can consist of multiple f-flows but includes at most one O- and at most one D-flow.

Since in our model we require, that every origin-destination flow of the given transportation volumes W is being operated, the flows from the origin node to the first hub and the according flows from the last hub to the destination node can be calculated by $O_i = \sum_{j\epsilon N} w_{ij}$ and $D_j = \sum_{i\epsilon N} w_{ij}$ respectively (Alumur et al. 2009).

The goal of the model is to determine where in the network to establish hubs and what type of terminal should be installed in order to handle all given flows at minimum overall costs. Therefore the model also has to allocate every non-hub node to a hub and route the flows through the network in a cost optimal way.

The objective function minimizes the overall system costs which consist of transportation costs as well as fixed operating and variable cargo handling costs at the terminals.

In the first term of the objective function (1a) the costs of the road transportation from the origin nodes to the associated hubs are calculated. This is followed by the costs for delivering a flow from the last hub to the destination node by truck. (1b) evaluates the costs of routing a flow from hub to hub within the railway system. (1c) regards for the fixed costs that arise when a hub of a certain type is being operated at node k. In (1d) the costs that are caused by handling flow at a hub are considered. As one can see (1d) is nonlinear and can therefore make the model hard to solve. So in (1e) a linearized version of (1d) is proposed where $ld1_k^c$ is the linearization of $f_{lk}^i g_k^c$ and $ld2_{ik}^c = x_{ik} g_k^c$. The constraints for these linearizations are given in constraints (18) through (22).

In order to model the transportation costs we use distance-dependent cost functions for road and for rail transport based on the distance matrix C which result in costs of c_{ij}^{truck} and c_{ij}^{train} for the shipment of one unit of flow from node i to node j on a direct connection with the according mode of transportation. In case such cost functions are not available one can simply substitute c_{ij}^{truck} and c_{ij}^{train} with c_{ij} and add a discount factor α to the last term of (1a) as it is widely used in the literature in order to factor in the economies of scale associated with flows between hubs.

We do not consider costs for establishing hub-links since we assume that the transportation network is planned within an already existing railway network and therefore it is not necessary to include those costs. However, if desired this can easily be done by extending the objective function with the term

$$+ \sum_{k\in H} \sum_{l\in H: l>k} Cl_{kl}\, y_{kl} \tag{1e}$$

where Cl_{kl} are the costs for maintaining a hub-link between hubs at nodes k and l.

Constraint (2) allows to fix the number of hubs that should be operated in the system. As does constraint (3) for the according hub-links whereby this number has to be somewhere between $\mathrm{p}-1$, which is the minimum number of hub-links required to connect all hubs, and $\frac{(\mathrm{p}-1)\mathrm{p}}{2}$ which would provide a complete graph for all hub nodes. In order to let the model determine the number of hubs to be established one can simply leave out (2). The same applies to the number of hub-links and (3). Another obvious possibility would be to let the model determine the optimal number of hubs, but predetermine the connections between the hubs in a way that all hubs are connected with the minimum number of hub-links so that the graph of hubs takes the form of a spanning tree. This can be achieved by including

$$\sum_{k \in H} \sum_{l \in H} y_{kl} = \sum_{k \in H} x_{kk} - 1 \tag{33}$$

into the model.

Constraint (4) makes sure that the single allocation condition is met and every non-hub node is allocated to exactly one hub. Additionally (5) ensures that non-hub nodes are only allocated to hub nodes. Constraints (6) and (7) guarantee that hub-links can only be established between actual hubs and not between non-hub nodes. (8) is the flow conservation constraint and makes sure, that every flow that enters a hub is routed further through the system, except for flows that are designated for the node of the hub. For strictly non-negative $\mathrm{f}_{\mathrm{kl}}^{\mathrm{i}}$-flows and in order to ensure that they are only positive if nodes k and l are hubs (10) and (9) are added to the model.

Constraint (11) offers the possibility to limit the maximum amount of flow that can be routed over a specific hub-link to a certain capacity Θ. However, since in the context of train operations the track capacity usually is not a limiting factor, it can be included or left out as needed. In contrast to (11), constraint (12) serves the purpose of limiting hub-link operations to connections that exceed a certain amount of flow. This constraint can be motivated by the fact, that in reality it is not feasible to establish train routes where there is not enough cargo traffic to operate a minimum number of trains per week. Subsidiary to that, (13) prevents the model to send flow back and forth a hub-link in order to push the volume of flow over the minimum flow requirements threshold where n can be any big number that is known to exceed the actual flow. Since (13) is a non-linear constraint which can cause difficulties when solving the model, (14) provides a linearized version of the constraint where $ld3_{ijk} = x_{ik}x_{jk}$. Linearization constraints are given in (23)-(25).

The following two constraints present the possibility to include different hub types in the model which can be differentiated according to their flow capacity as well as their fixed operating costs and the cost for transshipping units of flow. (15) limits every hub to exactly one hub type out of the subset $L = \{1, \dots, c\}$ of possible types of hubs. That the capacity of a hub of a certain size is not exceeded is ensured via (16). Through (17) different types of hubs can be further differentiated by limiting the number of hub-links that can be connected to a hub of type $c \in L$ to a fixed number of a.

Finally constraints (26) through (32) are non-negativity and binary conditions.

3. CASE STUDY

In this case study we apply our model to a test scenario that is based on the situation in the CEE - area. Therefore the model is implemented in the solver software Xpress, using the programming language Mosel.

For the case study we use real world data to build a simplified model that resembles the conditions of a transportation network in this area in terms of terminal sizes and costs as well as transportation volumes and distances plus costs for rail and road based transportation.

As data basis for the flow volumes we use yearly freight transportation data of the CEE region on a NUTS2 regional level. The data regarding costs and capacities of terminals are based on the information of experts involved in intermodal transportation and terminal operations. For modeling the intermodal transportation costs we use distance-dependent cost functions where the costs per km decrease with increasing transport distance. The cost function for train-based transport starts at 80 per cent of the costs for road transportation and includes a higher cost degression. To be eligible for the establishment of a hub-link, we require a minimum amount of aggregated flow on a hub-hub connection, roughly corresponding to one block train per week operating on the hub-link. In order to create our network area, we generate 20 random nodes on a coordinate system to resemble the actual CEE region and calculate the resulting distances between these nodes. We also choose ten nodes to be potential hub locations.

The resulting map of nodes looks as depicted in figure 3. Colored nodes indicate that the node is marked as potential hub location.

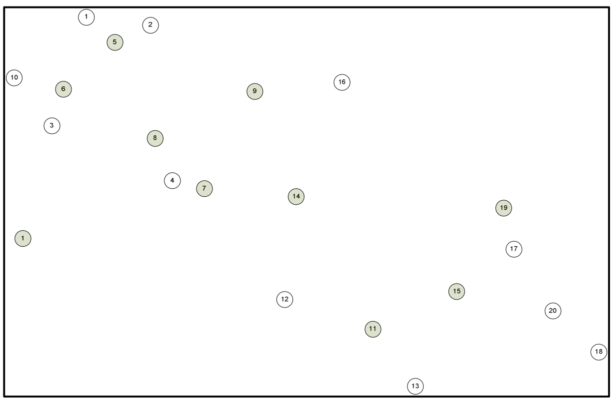

Figure 3: Map Of Nodes

Solving the optimization model leads to a network of seven hubs that are connected with eight hub-links. Figure 4 shows the resulting network where rectangular nodes indicate hubs and red lines mark hub-links. In the optimal solution out of the three possible terminal types, only medium and small capacity hubs are used. Medium sized hubs are located at the nodes 5, 6, 7 and 14 whereas at nodes 8, 9 and 19 small hubs are established. The fact, that there are no large hubs placed into the network leads to the conclusion that the operation of a larger amount of smaller hubs is favored over the possibility to use fewer hubs with higher capacity. This can be explained by the fact that in our network the transportation costs outweigh the costs of terminal operations by far. In the optimal configuration of the network, terminal related costs account for 10% of the overall costs while the other 90% are shipment costs. So it is hardly surprising that the savings in shipment costs that come with a larger amount of hubs and thus a reduced mileage for truck shipments lead to a relatively high number of hubs in the network. Especially since we focus on the operation of the network and thus do not consider investment costs for the installation of a hub.

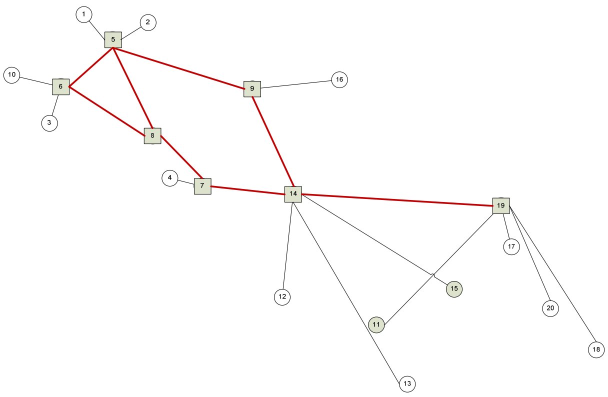

Figure 4: Solution 1 Of The Hub Location Problem

Varying the costs for transportation shows, that the network design is sensitive to the cost ratio of rail and road haulage. The higher the cost advantage of train transportation, the higher is the tendency to include additional hubs and hub-links to exploit those cost advantages.

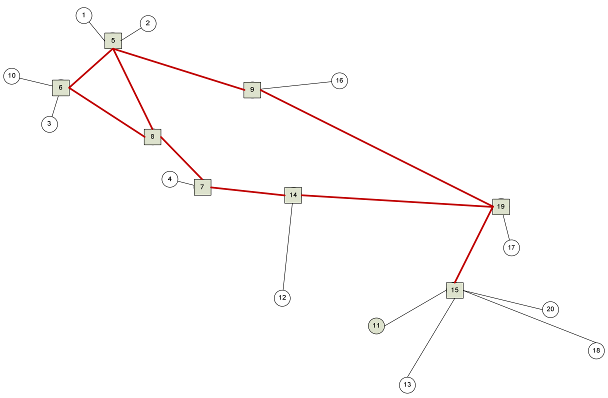

Figure 5: Solution 2 With Decreased Train Costs

A reduction of the cost ratio from 80% to 60% results in the inclusion of an additional hub at node 15 (see figure 5) whereas an increase to 90% leads to the subtraction of the hub at node 9 (see figure 6).

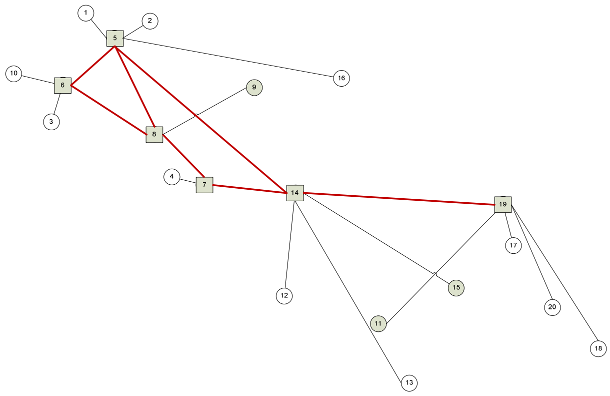

Figure 6: Solution 3 With Increased Train Costs

In a next step we restrict the model in the number of hub-links that can be established so that the resulting graph of hubs is a spanning tree. The underlying assumption is that the potential hub nodes are consecutively located along the main routes of the railway network and therefore cannot be bypassed via hub-links that connect other hubs in a more direct way.

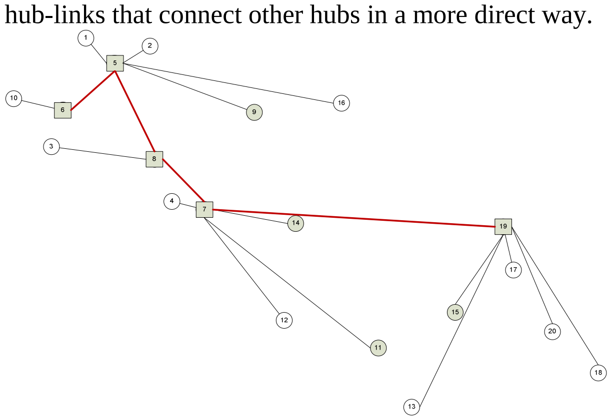

Figure 7: Solution 4 With Limited Hub Connectivity

Compared to the initial solution network this change results in the removal of two hubs (at nodes 9 and 14) from the model solution as shown in figure 7. This result is consistent with the previous findings. Since the possibility of saving shipment costs by directly linking hubs in order to shorten the transportation distances is limited now, it becomes less beneficial to operate a large hub network. So in this solution there is a terminal of the highest available capacity placed at node 5 and four medium sized terminals are operated at nodes 6, 7, 8 and 19. There are no small terminals established in the network any more.

Table 1: Relative Network Costs

	Relative Network Costs			
cost factor	**Solution 1**	**Solution 2**	**Solution 3**	**Solution 4**
overall costs relativ to Solution 1	**100,0%**	**84,1%**	**104,5%**	**107,4%**
prehaulage	15,7%	12,8%	17,9%	17,6%
train tansport	61,1%	62,4%	57,0%	60,7%
posthaulage	13,7%	12,7%	16,0%	14,2%
transportation	**90,5%**	**88,0%**	**91,0%**	**92,6%**
fixed operating costs	6,2%	8,0%	6,1%	4,7%
transshippment	3,3%	4,1%	3,0%	2,8%
terminal operations	**9,5%**	**12,0%**	**9,0%**	**7,4%**

Table 1 compares the overall network costs of the presented solution networks relative to the initial solution 1. Additionally the shares of the different cost factors in the respective network costs are listed. One can see that the restrictions for the establishment of hub-link connections result in a seven per cent increase in total network costs while the shares of the cost factors are relatively constant.

4. CONCLUSIONS AND FURTHER RESEARCH

The results of our case study indicate that the model solutions are not very robust in terms of changes in the cost structure of road and railroad transportation as well as restrictions for the establishment of hub-links. So when planning an actual network it should be ensured that the used data as well as the modeling of these elements are as close to the real world situation as possible.

A general limitation of the presented approach lies in the static nature of the optimization and the use of aggregated data which makes it impossible to consider the variability of freight volumes and the implications for terminal capacities and train connections during peak and off-peak periods.

As the presented approach therefore only constitutes the first step in an integrated planning and evaluation framework, further research will mainly focus on the planning of the operational network design, including concepts for terminal operations and train production concepts, and their detailed assessment. Thus, for the completion of the overall process an agent based simulation model will be used for a comprehensive analysis of the networks designed according to the presented method. In other words, after the network topology is fixed and the transportation volumes are allocated to the different terminals in the network by optimization a multi-agent simulation model is applied for the evaluation at the tactical and operational levels.

Therefore we model the processes that take place at an intermodal terminal and the railway system that connects the terminals by using simulation techniques. Hereby we focus on processes that are specific to intermodal terminals like the handling of intermodal loading units and train dispatching. With the simulation tool, one can test different concepts of terminal operations as well as train production concepts and determine the correspondent performance measures like transshipment capacities and cycle times for train dispatching.

Hence the simulation model supplements the static results of the hub location optimization with dynamic performance parameters. The simulation enables the evaluation of capacity limits of the terminal network and allows to analyze the effects of different train production concepts. If this evaluation of the intermodal transportation system exposes flaws induced by the network topology or network operation concepts, the preceding steps of optimization and design can be repeated in feedback loops within the whole method framework.

REFERENCES

Alumur, S., Kara, Y., 2008. Network hub location problems: The state of the art. *European Journal of Operational Research*, 190: 1-21.

Alumur, S., Kara, Y., Karasan, E., 2009. The design of single allocation incomplete hub networks. *Transportation Research Part B 43*, 936-951.

Bierwirth, C., Kirschstein, T., Meisel, F., 2012. On Transport Service Selection in Intermodal Rail/Road Distribution Networks. *BuR Business Research Journal*, Vol. 5, No. 2:198-219.

Caris, A., Macharis, C., Janssens, G., K., 2013. Decision support in intermodal transport: A new research agenda. *Computers in Industry*, Vol. 64, No. 2:105-112.

Clausen, U., Sender, J., 2011. Hub location problems with choice of different hub capacities and vehicle types. In: Pahl, J., Reiers, T., Voß, S., eds. *Lecture Notes in Computer Science 6701*, 535-546.

European Commission, 2005. Trans-European Transport Network, *TEN-T priority axes and projects.* European Commission, Energy and Transport DG. Brussels.

Floden, J., 2007. *Modelling Intermodal Freight Transport – The potential of Combined Transport in Sweden*. Doctoral Thesis. Göteborg University.

Gambardella, L.M., Rizzoli, A.E., Funk, P., 2002. Agent-based planning and simulation of combined rail/road transport. *Simulation*, 78, No 5: 293-303.

Gronalt, M., Posset, M. Rojas-Navas, T., 2012. Capacity Evaluation of Inland Container Terminals – The Simulation Based Approach of SimCont. *Proceedings of the 2012 International Conference on Logistics and Maritime Systems.* August 22-24, Bremen (Germany).

Macharis, C., Bontekoning, Y. M., 2004. Opportunities for OR in intermodal freight transport research: A review. *European Journal of Operational Research*, 153: 400-416

Rizzoli, A.E., Gambardella, L.M., Funk, P., 2002. A simulation tool for combined rail/road transport in intermodal terminals. *Mathematics and Computers in Simulation*, 59: 57-71.

Schindlbacher, E. und Gronalt, M.,2010. Using Auction Mechanisms for Coordinating Container Flows in Intermodal Freight Transport Networks. *Proceedings of the 2010 European Simulation and Modelling Conference*, 317-321, October 25-27, Hasselt (Belgium).

Seidelmann, C., 2010. 40 Jahre Kombinierter Verkehr Straße-Schiene in Europa – Vom Huckepackverkehr zum Intermodalen Transportsystem. *Internationale Vereinigung der Gesellschaften für den kombinierten Verkehr Schiene-Straße.* UIRR. Brussels.

UIC, 2010. DIOMIS – Evolution of intermodalrail/roadtraffic in Central and Eastern European Countries by 2020. *Management Report – Developing Infrastructure & Operating Models for Intermodal Shift.* International Union of Railways, Paris.