Service network design for an intermodal container network with flexible due dates/times and the possibility of using subcontracted transport

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Abstract
An intermodal container transportation network is being developed between Rotterdam and several inland terminals in North West Europe: the EUROPEAN GATEWAY SERVICES (EGS) network. This network is developed and operated by the seaports of EUROPE CONTAINER TERMINALS (ECT). To use this network cost-efficiently, a centralized planning of the container transportation is required, to be operated by the seaport. In this paper, a new mathematical model is proposed for the service network design. The model uses a combination of a path-based formulation and a minimum flow network formulation. It introduces two new features to the intermodal network-planning problem. Firstly, overdue deliveries are penalized instead of prohibited. Secondly, the model combines self-operated and subcontracted services. The service network design considers the network-planning problem at a tactical level: the optimal service schedule between the given network terminals is determined. The model considers self-operated or subcontracted barge and rail services as well as transport by truck. The model is used for the service network design of the EGS network. For this case, the benefit of using container transportation with multiple legs and intermediate transfers is studied. Also, a preliminary test of the influence of the new aspects of the model is done. The preliminary results indicate that the proposed model is suitable for the service network design in modern intermodal container transport networks. Also, the results suggest that a combined business model for the network transport and terminals is worth investigating further, as the transit costs can be reduced with lower transfer costs.

Keywords: Intermodal planning, synchromodal planning, network optimization, container transportation

1. Introduction

1.1. Development of container networks

A tendency of more integrated supply chains has sparked initiative in North-West Europe to create transportation networks for containers (Groothedde et al., 2005, Lucassen and Dogger, 2012, Rodrigue and Notteboom, 2012, Port of Rotterdam, 2012). These container transportation networks are generally formed by the cooperation of multiple barge service operators, rail service operators and terminals. Roso et al. (2009) defined the concept of a *dry port*: “a hinterland terminal in close connection to the sea port, where customers can leave or pick up their standardized units as if directly at a seaport.” Based on this concept, Veenstra et al. (2012) introduced the concept of an *extended gate*: a dry port for which the seaport can choose to control the flow of containers to and from that inland terminal. This control by the seaport distinguishes the extended gate from a dry port as defined by Roso et al. (2009) and introduces a central management for the intermodal container network. This concept has been implemented in the EUROPEAN GATEWAY SERVICES (EGS) since 2007, a subsidiary of EUROPE CONTAINER TERMINALS (ECT) with three seaports in Rotterdam. The network consists of these three seaports and an increasing number of terminals in North-West Europe (see Figure 1). Customers of the network operator do not book transports on specified services, but place orders with specific delivery time requirements. The network operator accepts orders without regarding the service schedule, considering some threshold (e.g. a minimum delivery time of 24h). Subsequently, the orders are planned on the transportation network, minimizing costs and satisfying delivery time requirements as much as possible.

Figure 1 Overview of connections in the EGS network [EGS, 2012]

1.2. Definitions: intermodal and synchromodal

The network of Figure 1 shows hinterland connections between Rotterdam (where the three seaport terminals are located) and the inland terminals (status 2012). This study focuses on the transportation from the seaport terminal to a hinterland terminal (import) or vice versa (export), organised by the sea port terminal and final drayage to a customer is excluded. This is called *hinterland transportation*. In the network, transport is carried out by three different *modes*: barge, rail and truck. Hence, as different modes can be selected, the transportation in the network is considered *multimodal transportation*. At terminals, containers can be exchanged from one mode to another. In scientific literature, the term transhipment is used for all types of exchange. However, to prevent confusion with the common practice in the Rotterdam port, the following definitions are used throughout this paper. An exchange at a terminal is called *transhipment* if the container is exchanged from one ship to another and *transfer* if other modes are involved. Figure 2 shows a schematic view on three terminals. The figure shows five mode-specific *corridors* by which the terminals are directly connected. As multiple modes connect two terminals, multiple corridors exist. Terminal A and C are indirectly connected via terminal B, and transport is possible using the corridors to B and then to C. Each of the transport steps from one terminal to another is called a *leg*. The two consecutive legs are referred to as a *connection* between A and C. The *service* on a corridor between terminals is the movement of a vehicle from one terminal to another, following a specific *route*. The number of services per time period on a certain route is called the *service frequency*. EGS uses frequency to denote the number of services per week on a corridor. The specific path of a container, including the terminals and services used, is called an *itinerary* (Crainic and Kim, 2007) or a *path*.

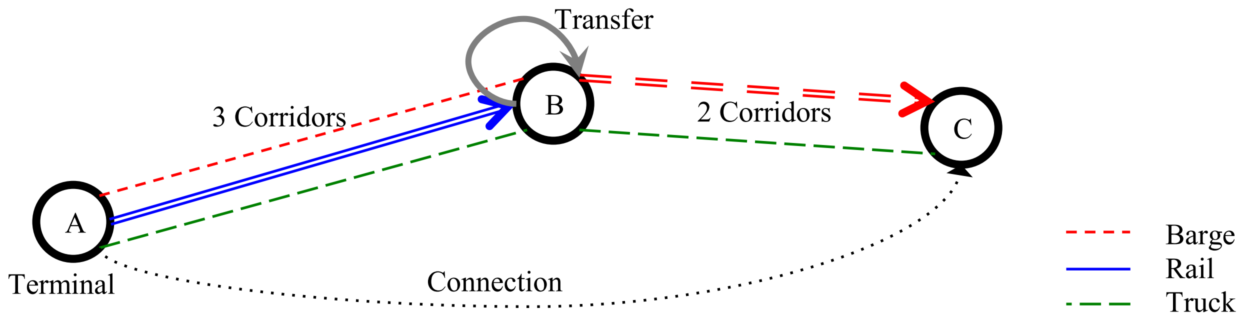

Figure 2 Container transport (schematic)

The transport between the hinterland location, e.g. a warehouse, and the inland network terminal is carried out by truck in most cases. Hence, most containers are transported using multiple consecutive services. This is referred to as intermodal transportation. Intermodal transportation is defined as *Multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes* (UNECE et al., 2009). The central management of the network allows for central intermodal network planning. With *intermodal network planning*, the routing of containers with multiple consecutive services is possible, using *intermediate transfers* of the containers at network terminals. In this study the term *intermodal transfer* is used for a transfer between different modes. A container that has an itinerary with two services uses such an intermodal transfer. Throughout this report, a transfer within the network is considered an *intermediate transfer*.

On top of that, a network with centrally planned transportation can use *real-time switching* (Lucassen and Dogger, 2012). Real-time switching refers to changing the container routing over the network in real-time to cope with transportation disturbances, such as service delays or cancellations. The combination of intermodal planning with real-time switching is often referred to as *synchromodal planning*, a new term on the agenda of the Dutch Topsector Logistiek (2011). However, no unambiguous definition for synchromodality exists yet. In this study, the following definition for synchromodal planning is used: *intermodal planning with the possibility of real-time switching between the modes* or online intermodal planning. As network transport orders with specific delivery time requirements are accepted, the use of synchromodal planning is essential for the network performance. This study focuses on the first part of synchromodal planning: the use of intermediate transfers in the intermodal planning. For that reason, the service network design is assessed, considering additional corridors between inland terminals and container transportation over paths with multiple consecutive legs and intermediate transfers.

1.3. New aspects of the proposed model

In this paper we propose a new mathematical model for the tactical service network design of intermodal container networks. It is important to investigate the cost-impact of using intermediate transfers on the service network design, because the seaport controls both transportation and terminal activities in the currently developing networks. Existing intermodal planning models do not suffice for this purpose for two reasons:

1. Current models use time restrictions for delivery. However, the extended gate network accepts network orders with time restrictions that can be freely planned on the available services. The daily practice in the container transportation (at EGS) is that planners and customers agree in mutual consultation on delivery times. Depending on the circumstances (transportation volume, disturbances) they are flexible in their negotiations. This cannot accurately be modelled by strict due time restrictions.
2. Moreover, existing service network design models focus on the selection of self-operated services in

the network. But container transportation networks use a combination of self-operated services and subcontracted services.

In the case of self-operated services, the network operator pays for the entire barge or train and incurs no additional transportation costs per TEU (twenty feet equivalent unit, a standardized container size measure). In the case of subcontracted transportation, transportation is paid for per TEU. Nonetheless, the loading and unloading of containers (handling costs) does have a cost per TEU for both cases.

The service network design model proposed in this study introduces two new aspects to the service network design problem:

1. Overdue delivery is not restricted, but penalized by a penalty per TEU per day of overdue delivery.
2. The model allows for a combined use of self-operated and subcontracted services.

1.4. Structure of the paper

This paper is organised as follows. Section 2 briefly reviews literature on service network design models. Section 3 introduces the proposed intermodal container network model. The case of EGS is used as an example for the intermodal container network model of this study in Section 4. The results of the experiments are discussed in Section 5. Section 6 concludes the paper and proposes further research.

2. Literature review

In academic literature, three levels of network planning are distinguished (Crainic and Laporte, 1997, Macharis and Bontekoning, 2004): strategic, tactical and operational planning. The exact boundary between these levels often depends on the point of view of the planning. In general, strategic planning focuses on long-term network design, such as locations of terminals or transport hubs (e.g. Ishfaq and Sox, 2010). Kagan (2012) provides an overview of the *hub-location problem*. Operational planning focuses on the day-to-day planning of network transportation (e.g. Jansen et al., 2004, Ziliaskopoulos and Wardell, 2000). An overview is provided by Crainic and Kim (2007). This paper focuses on a tactical level planning, the service network design. Service network design consists of the following aspects as described by Crainic (2000): the selection and scheduling of the services to operate, the specification of the terminal operations and the routing of freight. Network design models are often mixed-integer problem-based formulations of a network structure where nodes represent terminals and arcs represent services (Crainic, 2000). When multiple modes can travel between the same network terminals, multiple arcs are used to represent these corridors. Both the assignment of cargo to routes and the number of services on each corridor are considered simultaneously. In the existing literature about intermodal container transportation networks, several service network design models have been proposed. Two types of models can be distinguished:

- Minimum cost network flow models (MCNF)
- Path-based network design models (PBND)

Both types of models are able to consider capacitated flow and multiple commodities (see Table 1). In this sense a commodity, or equivalently cargo class, is used to denote a set of containers that have equal properties, such as mass, origin, destination and delivery time.

Table 1 Examples of existing service network design models

	MCNF	PBND
Single commodity	Ziliaskopoulos (2000) Holmberg and Hellstrand (1998)	
Multi-commodity	Crainic & Rousseau (1986) Crainic (2000) Ishfaq & Sox (2010, 2012)	Crainic & Rousseau (1986) Crainic & Laporte (1997) Crainic (2000)

MCNF models have the possibility of flexible routing of cargo over various links in the network. Also, explicit constraints on the link capacity can be set. However, the main disadvantage is the number of decision variables for multi-commodity, multi-mode formulations. A variable is required for each cargo class on each arc. For applications with many origin-destination pairs, mass categories and delivery times, the number of

decision variables becomes too high for practical computation times. For PBND type of models, the possible paths for each cargo class are predetermined. A path is the exact route of a container using subsequent services and terminals. This reduces the number of decision variables significantly, provided that the number of possible paths is kept at a low enough number. However, with the traditional PBND formulations, the capacity of services travelling on each arc cannot be restricted directly, as multiple paths for the same or different cargo classes coincide on single services. The model proposed in the next section uses a formulation that combines the arc capacity restrictions with the routing of containers over predetermined paths, as suggested by Crainic (2000).
Some of the existing tactical service network formulations use strict constraints on delivery time (Ziliaskopoulos and Wardell, 2000) or no due time restrictions (e.g. Crainic, 2000). Strict constraints do not accurately model the flexibility that transportation planners have in consultation with customers. No time restrictions at all neglect the existing time pressure in the container transportation. The proposed model uses an alternative formulation that better suits the flexible delivery time restrictions.
Several models use formulations that model the economies of scale that occur when cargo is consolidated on an arc (e.g. Ishfaq and Sox, 2012). These abstract formulations of economies of scale cannot directly represent the current situation. The current practice in intermodal container networks is that multiple service and terminal operators cooperate and in this perspective, economies of scale are exploited by selecting services operated by the network operator (self-operated services) or use subcontracted transport. The difference in cost structure between these two cannot be modelled in the existing formulations for the economies of scale. Hence, the proposed model allows for a combined use of self-operated and subcontracted services.

3. Proposed model

To solve the service network design problem, the optimal number of services on all corridors in the network must be determined, referred to as the service schedule in the remainder of this paper. Note that a service schedule would also require determining the departure times during the week, but that is out of scope of the model. Determining the optimal service frequencies is done by the central network operator and is evaluated every couple of months. The objective is to create a single weekly service schedule that minimizes the weekly transportation costs for a set of expected demand patterns. So, the service schedule is determined while considering a set of demand patterns Q. A *cargo class* is a group of containers with equal origin and destination, the same weight class and with the same period for delivery (due time). Each pattern $q \in Q$ consists of an expected transportation volume for each cargo class $c \in C$. The expected transportation volume of cargo class c in demand pattern q is denoted by $d_{c,q}$ (in TEU). For each cargo class c the parameters w_c and t_c denote the weight and due time of that cargo class, respectively.
The model is formulated as a mixed-integer linear programing problem with a linear objective and linear constraints. It combines aspects of the MCNF and PBND formulations described in the previous section (e.g. by Crainic, 2000). Moreover, two aspects are added: the possibility for overdue delivery, at the cost of a penalty, and the possibility of using self-operated and subcontracted transportation. The objective minimizes the weekly transportation costs consisting of four cost terms:

- The cost of operating the self-operated services
- The cost of subcontracted transportation
- Transfer costs (loading and unloading containers)
- Penalties for overdue delivery

The possible paths in the network for each cargo class must be predetermined. This can be done in various ways, such as using the expert knowledge in existing networks, or by an automated path generation method as is used in the case study of the next section. The set of all possible paths is denoted by P. The subset of feasible paths for each cargo class c is denoted by P_c. In this study a path is considered feasible for cargo class c if the origin and final destination coincide. The weight of containers in a cargo class could be added as an additional criterion for a path's feasibility.
The model uses four sets of decision variables. The (integer) service frequencies y_{ijm} denote the number of self-operated services between terminal i and j with mode m, defined as *corridor* (i, j, m). The set of available corridors is denoted by A. The service frequencies are determined while considering multiple demand patterns $q \in Q$. The amount of TEU of cargo class c on self-operated or subcontracted services on corridor (i, j, m) in

pattern q is denoted by the flow variables $z_{ijm}^{c,q}$ and $\zeta_{ijm}^{c,q}$, respectively. Finally, the path selection variable $x_p^{c,q}$ denotes the number of TEU of cargo class c transported on path p in pattern q. The objective of the model is to minimize the following objective function J:

$$J = \sum_{(i,j,m)\in A} f_{ijm}\, y_{ijm} + \sum_{(i,j,m)\in A} \sum_{(c,q)\in C\times Q} c_{ijm}\, \zeta_{ijm}^{c,q} + c_F \sum_{p\in P} F_p \sum_{(c,q)\in C\times Q} x_p^{c,q} + c_\tau \sum_{(c,p)\in C\times P} \tau_p^c, \quad (1)$$

where

- f_{ijm} and c_{ijm} denote the costs of operating a service or subcontracting one TEU on corridor (i,j,m), respectively,
- c_F is the cost per transfer,
- F_p is the number of transfers on path p;
- c_τ denotes the cost per TEU for each day late delivery.

Hence, the first term of the objective represents the cost for the selected services to operate self; the second term sums all costs for subcontracted transports in all patterns q; the third term denotes the costs for transfers and the fourth term is the penalty cost for overdue delivery.
The minimization of objective function J is subject to constraints: all transportation demand must be fulfilled, while meeting the capacity restrictions of the selected services. The TEU-capacity and maximum weight of a service on corridor (i,j,m) is denoted by u_{ijm} and m_{ijm}, respectively. Besides, the allocation of containers to paths, $x_p^{c,q}$, must be translated to the allocation of containers to services, denoted by the flow variables $z_{ijm}^{c,q}$ and $\zeta_{ijm}^{c,q}$. This mapping of selected paths to the flow variables is done with δ_{ijm}^p, which is 1 if the corridor *(i,j,m)* is on path *p and zero else*. The constraints of the model are formulated as follows:

$$\sum_{p\in P_c} x_p^{c,q} = d_{c,q} \qquad \forall (c,q) \in C \times Q \quad (2)$$

$$\sum_{p\in P} \delta_{ijm}^p x_p^{c,q} = z_{ijm}^{c,q} + \zeta_{ijm}^{c,q} \qquad \forall (i,j,m) \in A;\ \forall (c,q) \in C \times Q \quad (3)$$

$$\sum_{c\in C} z_{ijm}^{c,q} \le u_{ijm} y_{ijm} \qquad \forall (i,j,m) \in A;\ \forall q \in Q \quad (4)$$

$$\sum_{c\in C} w_c z_{ijm}^{c,q} \le m_{ijm} y_{ijm} \qquad \forall (i,j,m) \in A;\ \forall q \in Q \quad (5)$$

$$\sum_{q\in Q} x_p^{c,q} \left(T_p - t_c\right) \le \tau_p^c \qquad \forall (c,p) \in C \times P \quad (6)$$

$$y_{ijm} = y_{jim} \qquad \forall (i,j,m) \in A \quad (7)$$

$$x_p^{c,q} \ge 0 \qquad \forall (c,q) \in (C \times Q);\ \forall p \in P \quad (8)$$

$$\tau_p^c \ge 0 \qquad \forall (c,p) \in C \times P \quad (9)$$

$$z_{ijm}^{c,q} \ge 0, \zeta_{ijm}^{c,q} \ge 0 \qquad \forall (i,j,m) \in A;\ \forall (c,q) \in C \times P \quad (10)$$

$$y_{ijm} \in \mathbb{N} \qquad \forall (i,j,m) \in A \quad (11)$$

Here, constraint (2) ensures that all transportation demand is met in all patterns. The allocation of the demand to the paths is mapped to the flow variables by Constraint (3). This mapping depends on the used services (self-operated or contracted) in the predefined paths. Constraints (4) and (5) are the capacity constraints on each corridor, dependent on the selected number of services. Note that the capacity on subcontracted services is considered unlimited in this formulation. Constraint (6) ensures that the auxiliary variable τ_p^c equals the total number of overdue days for all TEU of cargo class c on path p, by measuring the difference in the available delivery period t_c and the predetermined path duration T_p. If cargo class c is on time using path p, Constraint (9) ensures that τ_p^c is equal to zero. Constraint (7) is the balance equation for the used equipment for self-operated services: it ensures the same number of self-operated services back and forth on a corridor, to keep the equipment balanced over the network. Finally, Constraints (8)-(10) ensure the nonnegativity of the other variables and Constraint (11) restricts y_{ijm} to the integer set of natural numbers.

4. Case study of EGS

4.1. Network and paths

The model is applied to the real-world case of the network transportation in the EUROPEAN GATEWAY SERVICES network. The EGS network has been continuously growing with terminals and connections (EGS, 2012). This study's focus is on the network situation of June 2012: it consists of three ECT seaports in Rotterdam (Delta, Euromax and Home) and seven inland terminals in the Netherlands, Belgium and Germany, i.e. Moerdijk, Venlo, Willebroek, Duisburg, Dortmund, Neuss and Nuremberg. All terminals can accommodate barge, rail and truck services, with a few exceptions: Willebroek and Moerdijk cannot accommodate train services; Dortmund and Nuremberg do not have a barge terminal.

Before the model can be applied to the service network design for this network, suitable paths must be predetermined. The number of possible paths could grow exponentially with the number of terminals in the network. However, in order to solve the model in a reasonable amount of time, some smart path selection was applied to restrict the number of possible paths. Suitable paths between all locations are predetermined using the *k-shortest path* method by Yen (1971). This method is able to select shortest paths without loops in a network, based on Dijkstra's algorithm. In this study, the number of selected paths was restricted using the following three rules, all based on practical experience at the EGS planning department:

- Paths are selected based on the geographical length of the network arcs, up to a length of three times the length of the shortest path. Longer paths are considered unrealistic for use in practice. The geographical length of a network arc is measured as the length of the truck route on that arc.
- Subsequently, omitting all paths that consist of more than three transportation legs reduces the number of paths further. More than two intermediate transfers are not considered in this study.
- Then, paths that have a detour of more than 10% in any of the transportation legs are omitted. This detour is measured as the difference in distance to the destination from both ends of a leg. Let T_{kD} denote the trucking distance from node k to the destination. Then, a path is considered to make a detour if $T_{iD} \geq 1.1T_{jD}$ in any of its legs (i, j). This rule is added to prevent paths with unrealistic detours, a little detour is allowed, though.

All of the remaining paths describe a geographic route with one to three transportation legs in the network. The final step of the path generation is to generate all intermodal possibilities of such a route, based on the possibility of barge and train corridors between the network locations. Truck is only considered for the last (first) leg before (after) the hinterland destination (origin), as it does not make sense to do truck transfers. E.g. a route Rotterdam Delta → Venlo → Nuremberg results in four paths (see Figure 3) :

$$
\begin{array}{lllll}
\text{Delta} & \xrightarrow{barge} & \text{Venlo} & \xrightarrow{rail} & \text{Nuremberg,} \\
\text{Delta} & \xrightarrow{rail} & \text{Venlo} & \xrightarrow{rail} & \text{Nuremberg,} \\
\text{Delta} & \xrightarrow{rail} & \text{Venlo} & \xrightarrow{truck} & \text{Nuremberg,} \\
\text{Delta} & \xrightarrow{barge} & \text{Venlo} & \xrightarrow{truck} & \text{Nuremberg,}
\end{array}
$$

where both Delta and Venlo have a rail and barge terminal, but Nuremberg does not have a barge terminal. Note that the truck mode is only considered for the last leg. With each path p is associated a travel time T_p and a number of transfers F_p. In the EGS case study, this method of path selection between all network terminals results in a set of 13977 paths.

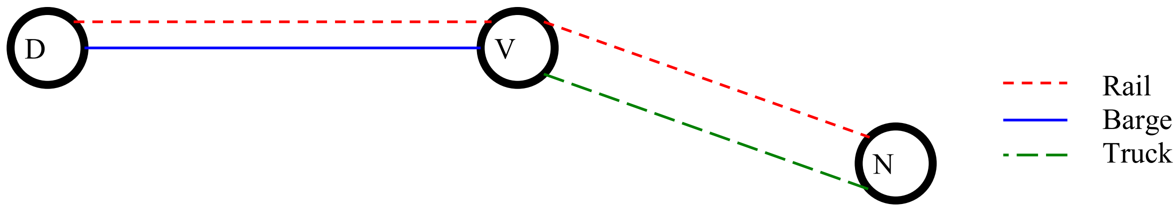

Figure 3 Four intermodal paths on Delta → Venlo → Nuremberg (schematic)

4.2. Costs and transportation demand

The cost parameters in the study are based on the actual costs in the current operation of the EGS network. To protect the confidentiality of the data, all costs in this paper are masked by a confidentiality factor.

The corridor costs per service (f_{ijm}) and per TEU (c_{ijm}) are modeled with a linear approximation of the actual network costs and the corridor length d_{ijm}, i.e. $c_{ijm} = \alpha d_{ijm} + \beta$. For each transfer a cost of $c_F = 23.89$ is used. The cost of overdue delivery per TEU per day is $c_\tau = 50$. The transportation costs used in the experiments of this study are reported in Appendix A.

For this case study, the expected demand is determined based on the historic transportation volumes. An analysis of the transportation on the EGS network in the period of January 2009 - June 2012 did not show significant periodic behaviour, so periodic demand fluctuations can be neglected. The weekly transportation volumes are tested for normality. As the transported volume grew fast in 2010, the weekly demands were further analysed based on the period January 2011 - June 2012. Using Pearson's χ^2 Goodness-of-fit test (Cochran, 1952), the hypothesis of normality of the distribution of the weekly volume was accepted with a p-value of 0.93.

Hence, the expected demand patterns for all cargo classes are based on the estimated normal distribution of transportation volumes in the period January 2011-June 2012. The parameters of the normal distribution of the weekly volume are determined for each cargo class. With this, ten 10-percentile subsets of the normal distribution are generated for each cargo class. These demands are used as ten patterns q in the proposed model. The model will determine the optimal service frequencies simultaneously, optimized for all ten 10-percentile sets.

5. Experiments

5.1. Scenarios

The model is solved for the EGS-case with AIMMS 3.12, using CPLEX 12.4, on a MacBook Pro with a dual core 2.66GHz processor and 8GB of RAM memory. Four different experiments are carried out. The service network design of the current EGS situation is considered the *basic scenario.* The other three experiments are hypothetical situations to assess the importance of the different aspects of the current model:

- It is interesting to investigate the relation between transfer costs and the use of intermediate transfers. Therefore, a scenario where the transfer costs are lowered by 50% is studied to find the effect of transfer costs on the service schedule
- The proposed model introduces the use of flexible due times. So, a scenario is considered where due times are ignored, or equivalently, the overdue costs are set to zero. This shows the impact of due times on the results.
- The proposed model also introduced the combination of self-operated services and subcontracted transport. To show the importance of this, a scenario without the possibility of selecting subcontracts is assessed. This shows the impact of using subcontracts along with the network services.

For the experiments carried out, also the CO_2-emissions are estimated, based on the STREAM-report by CE Delft (Den Boer et al., 2008). The used emissions are reported in Appendix B. The CO_2-emissions are reported as a cost, using a price of €8 per tonne CO_2, based on the price of an EU emission allowance for 1 tonne CO_2 as reported by Bloomberg in August 2012 (Bloomberg 2012).

5.2. Results

The results of the EGS case and the three hypothetical scenarios are shown in Table 2. The table shows the

resulting costs in total and separately for the four objective terms. Also, the computation times to carry out the experiments are shown.
The table shows that a large part of the weekly network transportation costs are for the handling of containers (transfer costs). These do not vary much between the various experiments; apart from the scenario were the transfer costs are reduced by 50%, obviously. In that case, the number of transfers increases by 4.1%. It can also be seen that the *transit costs*, the costs for self-operated or subcontracted transportation, does vary between the four experiments. That means that the service network design is sensitive to the tested parameters in the experiments. The CO_2 emissions in all four cases were very similar. In order to compare this with the reported cost in Table 1, the costs are masked with the confidentiality factor, resulting in a total CO_2 cost of 9.

Table 2 Results case study EGS

Cost terms	Total	Self-operated	Subcontracted	Transfers	Overdue	Comp. time [s]
Basic scenario	1142	223	163	632	122	119
50% transfer costs	818	201	166	329	122	111
No due times	946	206	103	638	0	106
No subcontracts	1424	636	0	634	153	4067

As an example, the resulting service frequencies and transportation volumes of the basic case solution are shown in Figure 4. To protect the confidentiality of the data, only the minimum and maximum of the transportation volume is reported, both masked with a confidentiality factor.

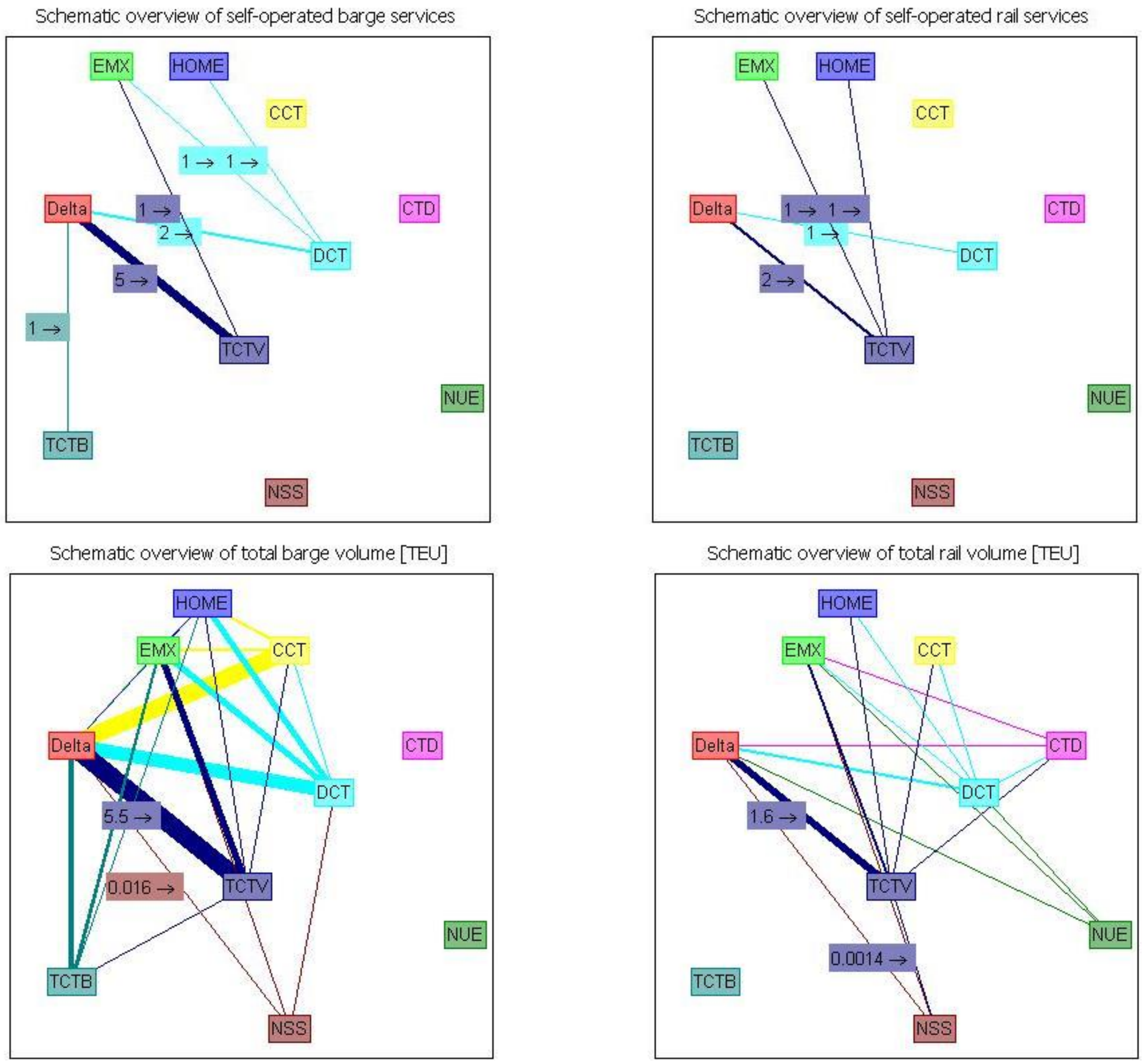

Figure 4 Service schedule in basic case

5.3. Discussion

The scenario with 50% transfer costs obviously has lower costs for transfers. However, also the transit costs (i.e. the costs for self-operated services and subcontracted transports) are reduced by 7.3%. The number of containers for which an intermediate transfer takes place increases from 1.2% to 5.4%. These results suggest that the network operator must look into the combined business model of services and terminals. Terminals with low utilization of the available capacity can easily handle intermediate transfers, and in that way possibly reduce transportation costs.

The scenario in which due times are omitted also shows a reduction of transit costs, with 22%. Hence, in the studied base case 22% of the transportation costs are made in order to deliver on time. On top of that, in the basic case the model 'accepts' a fictional penalty of 10.6% for late delivery. This shows the importance of the overdue delivery flexibility introduced in the model.

The scenario in which subcontracted transports are not considered shows the importance of the combination of self-operated and subcontracted transports. Without subcontracted transports, the total transportation takes place with self-operated services. Operating all these services increases the transit costs with 61% compared to the basic case solution. Even then, the number of late containers increases with 25%.

The proposed intermodal container network model was able to solve the various experiments fast in most scenarios. Computation times were below 2 minutes, except for the case in which no subcontracts were allowed. Solving that hypothetical case took more than an hour. The regular solution time of minutes makes the model suitable for the service network design of the current problem instance. An acceptable solution time is not guaranteed for larger problem instances, but it is expected that the solution method behaves well for regular cases. The size of regular problems is expected to be relatively small: most container networks will focus on the industrial zones supplied from a certain seaport. Such a network will often comprise a limited set of terminals, such as in the shown case of EGS. With increasing problem sizes, the number of arc-related variables (y_{ijm}, z_{ijm}, ζ_{ijm}) increases quadratic with the number of terminals. The number of paths (and path-related variables $x_p^{c,q}$ and τ_p^c) could increase exponentially, but smart path generation based on experience or other insights can be applied to restrict the number of paths. This will depend on the specific case, though. If, however, a studied network is very large, it will often be possible to split the network in independent sub problems with no loss of generality. This option will depend on the specific geographical situation though.

Hence, it is expected that the model will perform well for regular problem sizes; and using smart path generation, the method is also expected to work well enough for larger problem instances. Regardless, the model is relevant from a theoretical point of view, e.g. it illustrates the importance of transfer costs in the case study.

6. Conclusions & Future research

In this paper we have proposed a new model for the service network design of intermodal container networks. The model combined aspects of MNCF and PBND formulations and introduced two new aspects to the service network design: flexibility for overdue delivery and the use of subcontracted transport alongside self-operated services. With this model we assessed the benefit of intermediate transfers in the container transportation paths. The following general conclusions are drawn for intermodal container networks, based on the results of this study:

- A reduction of transfer costs will also result in a reduction of transit costs, by the use of intermediate transfers. This suggests that a combined business model for network terminals and transportation provides opportunities for reducing transportation costs.
- The proposed model is suitable for the service network design in a modern intermodal container transport network.

Future research is planned to extent the results based on the proposed model. The research will focus on a further sensitivity analysis of the service network design for the transfer costs and the overdue delivery penalty. Also, the scalability of the model to larger problem sizes will be tested. The new aspects of the model may also be beneficial for planning at an operational level. Future research into using an adapted model to operational container network planning is intended as well.

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Appendix A: Network transport cost estimation

To be able to analyse the transportation in an EGS-type of network, general cost formulas are estimated. The general cost structures are based on the available costs in the EGS network. The cost structures are introduced per mode in the following sections. Note that both costs *per service*, as costs *per TEU* are determined. All costs reported in this appendix are masked by a confidentiality factor, to protect the confidentiality of the data.

Costs of self-operated services

To identify the costs to operate a service, two types of barges are recognized. Two examples in the current EGS network are used. Estimation is based on the weekly cost structures shown in Table 3. To estimate a cost per service, the monthly costs must be split over the number of trips per month. For the sake of simplicity, we'll use the following estimated number of services of a piece of equipment per connection to determine the cost per trip. This assumption is considered acceptable from a planning point of view, as the actual acquisition and planning of equipment is not part of the research. The number of trips is based on a 12km/h barge travel speed and 9 hour stop per terminal. Although this is a rough estimate, the numbers of services correspond to the actual number of trips on the corridors that are already in use.
Two types of trains are recognized: diesel trains and electric trains. In Table 4 three examples of the EGS network are shown, on which the service cost estimation is based. On certain connections no overhead lines are available. Here diesel trains are used; the price of these services will be estimated using the €7.60 per km. On other connections where electric trains can be used, a price of €11.43 will be used. The resulting costs per trip of the services from and to the Delta terminal are shown in Table 5.

Table 3 Barge costs

Barge type	Rhine-barge	Benelux-barge
Total fixed cost	8784€/wk	7083€/wk
Fuel per km	4.73€/km	1.79€/km

Train type	Electric train	Diesel train
Average costs per TEU	€11.43/km	€7.60/km

Table 4 Rail costs

Terminal	Distance from Delta [km]	Barge type	Barge costs [€/trip]	Train type	Rail costs [€/trip]
EMAX	5	Benelux	573	Electric	46
HOME	31	Benelux	776	Electric	266
CCT Moerdijk	58	Benelux	694	Diesel	562
CTD				Electric	3396
DeCeTe	242	Rhine	3340	Electric	2790
NSS	280	Rhine	3520	Electric	2938
NUE				Electric	8094
TCT Belgium	166	Benelux	1476		
TCT Venlo	215	Benelux	1564	Diesel	1528

Table 5 Transport from Delta to hinterland (v.v.) ***All other corridors are calculated similarly.***

Subcontracted transportation costs (per TEU)

The costs for subcontracted transportation are estimated with available EGS cost data. The results are reported in Table 6. These costs are without €23,89 transfer costs per TEU.

Mode	Cost (α€/ TEU)
Barge	$0.14d$
Rail	$1.53 + 0.16d$
Truck	$76.4 + 1.04d$

Table 6 Costs for subcontracted transport

Appendix B: CO_2-emissions

	Well-to-Wheel [g CO2/tonkm]	Energy usage [MJ/km]	CO_2 in energy W2T/T2W [g CO_2/MJ]	Mean utilization [-]	CO_2-emission [tonne CO_2 / km / service]
Truck (2 TEU)	98	10	14.2 / 73	0.33	0.88
Electric train (90TEU)	25	77	170 / 0	0.87	13
Diesel train (90 TEU)	32	188	14.2 / 73	0.87	16
Rhine barge (380 TEU)	34	363	14.2 / 73	0.65	32
Benelux barge (push convoy) [160TEU]	34	883	14.2 / 73	0.65	77

Table 7 Based on STREAM-report (Den Boer et al., 2008): CO_2-emissions