CIRRELT

Centre interuniversitaire de recherche
sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre
on Enterprise Networks, Logistics and Transportation

Service Network Design with Management and Coordination of Multiple Fleets

Jardar Andersen
Teodor Gabriel Crainic
Marielle Christiansen

July 2007

CIRRELT-2007-21

Bureaux de Montréal :
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
Pavillon Palasis-Prince, local 2642
Québec (Québec)
Canada G1K 7P4
Téléphone : 418 656-2073
Télécopie : 418 656-2624

www.cirrelt.ca

Université Laval
UQÀM Université du Québec à Montréal
HEC MONTRĒAL
École Polytechnique Montréal
Université de Montréal

Service Network Design with Management and Coordination of Multiple Fleets

Jardar Andersen[1,2,*] ,Teodor Gabriel Crainic[3], Marielle Christiansen[1]

[1] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, 7491 Trondheim, Norway

[2] Institute of Transport Economics, Gaustadalléen 21, 0349 Oslo, Norway

[3] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT), Université de Montréal, C.P. 6128, succursale Centre-ville, Montréal, Canada H3C 3J7 and Chaire de recherche industrielle du CRSNG en management logistique, ESG, Université du Québec à Montréal, C.P. 8888, succursale Centre-ville, Montréal, Canada H3C 3P8

Abstract. We present a new optimization model for the tactical design of scheduled service networks for transportation systems where several entities provide service and internal exchanges and coordination with neighboring systems is critical. Internal exchanges represent border crossings necessitating changes of vehicles, while the coordination with neighboring systems represents intermodal operations. It is assumed that strategic planning has indicated an approximate design of the service network, and the model presented in this paper determines departure times of the services such that throughput time of the flow in the system is minimized. The model is an extension of the Design-Balanced Capacitated Multicommodity Network Design model (DBCMND) that we label Service Network Design with Asset Management and multiple Fleet Coordination (SNDAM-mFC) because different vehicle fleets are modeled explicitly. The model is applied to a real-world problem considering planning of new rail freight services across borders. We analyze how synchronization with collaborating services and removal of border crossing operations impact the throughput time for the freight. We identify a significant potential for system performance enhancement from synchronization among collaborating services for the problem studied.

Keywords. Transportation, capacitated multicommodity network design, modeling, scheduled service network design, asset management

Acknowledgements. This work has received financial support from The Norwegian Research Council through the Polcorridor Logchain project. Partial funding has also been made available from the Natural Sciences and Engineering Research Council of Canada (NSERC) through its Discovery and Industrial Research Chair grant programs. We want to thank two anonymous referees for valuable comments that have improved the presentation of the paper.

---

* Corresponding author: jardar.andersen@iot.ntnu.no

Dépôt légal – Bibliothèque nationale du Québec,
Bibliothèque nationale du Canada, 2007

Introduction

During the last 20 years, road transport has increased its market share in European freight transport as in practically all other regions of the globe. The flexibility, speed, and reliability of trucking compared to rail transport are significant reasons for this. It is however official European Union policy to promote increased market shares of environmentally friendly transport solutions both for passenger and freight (European commission, 2001). Promoting maritime and rail-based intermodal transport is hence the main target for future modal shift. One possible policy instrument for this can be taxation like road pricing with the purpose of making road transport less attractive. Another instrument is the ongoing effort aiming at increased rail interoperability across borders.

Political support is however not sufficient to ensure success of intermodal transport solutions. These solutions need to offer competitive service quality and reasonable prices. Intermodal transport chains result in more complex operations than direct shipment by truck, as at least two modes of transportation, two carriers, and an intermodal transfer facility are involved. Each carrier within the intermodal chain must be efficient in terms of transportation time and reliability, but it is also crucial that transshipment between modes and transportation systems is performed efficiently. Transportation service providers are thus facing a more challenging situation than just a few decades ago, and survivability is becoming more dependent of intelligent planning, design, and execution of operations. For an introduction to planning issues in intermodal transportation, we refer to Crainic and Kim (2007) and Macharis and Bontekoning (2004).

Logistics and transportation are among the successful application areas of operations research. Optimization models have been applied for more than 20 years to generate and evaluate transportation service networks. The major issues in *service network design* are the selection and scheduling of services, the specification of terminal operations, and the routing of flow. Service network design models were surveyed in Crainic (2000), while applications of service network design can be found in Crainic *et al.* (1984), Crainic and Rousseau (1986), Farvolden and Powell (1994), Gorman (1998) and Keaton (1989, 1991, 1992), for example. Stochastic aspects of service network design are discussed in Dall'Orto *et al.* (2006) and Lium *et al*. (2006). Service network design models are increasingly becoming more sophisticated, and with increased computational capability and improved solution techniques, larger instances can be solved. Moreover, it is possible to incorporate more aspects into one model for simultaneous consideration. Compared to sequential approaches, where planning issues are treated separately, this offers the opportunity for more coherent solutions to tasks that are interrelated but which have been treated separately in an attempt to maintain tractability. In particular, the simultaneous determination of service networks and vehicle movements is a research issue that deserves increased focus, as a lack of synchronization of these issues may lead to inefficient vehicle utilization.

One attempt that has been made to integrate aspects of vehicle management to service network design models is introduction of design-balance constraints stating that the number of services or vehicles entering and leaving terminals should be balanced. Formulations requiring node balance on design arcs are denoted Design-Balanced Capacitated Multicommodity Network Design (DBCMND) models (Pedersen, 2006; Pedersen *et al*., 2007). Few applications exist for this model class. Smilowitz *et al.* (2003) present a DBCMND model for express package deliveries, Pedersen and Crainic (2007; see also Pedersen 2006) present a DBCMND model for intermodal rail, and Lai and Lo (2004) present a DBCMND model for passenger ferries in Hong Kong. The DBCMND formulation captures important aspects of real-world transportation planning and represents an improved methodology for the design of transportation services. Yet, the DBCMND formulation as presented in Pedersen *et al.* (2007) is only a first step since it addresses rather simple vehicle utilization issues while optimizing the service network. We propose a more comprehensive service network design model that improves the integration of vehicle management and service network design. We use the term *asset management* to highlight this enhanced integration.

The model that we present in this paper is a new optimization model for tactical design of scheduled service networks of transportation systems where several entities provide service and where the exchanges and coordination with neighboring systems is critical. We assume that an indicative service network has been determined at a higher-level planning level (e.g., using a frequency service network design model). The main issue in the optimization model we propose is to determine departure times of services in such a way that the throughput time for a given demand is minimized. All demand has to be satisfied, and all services needed to serve the demand have to be covered by the considered fleets of vehicles. Services that are covered by different fleets have to be coordinated (synchronized). Crainic (2000) differentiated between static service network design models targeting strategic/tactical analyses and time-dependent models with an explicit time representation of the system's dynamics. Because of the scheduling aspects in our planning problem, the model we propose has similarities with the time-dependent models in Crainic (2000).

Our focus on asset management and fleet coordination in service network design is motivated by the Polcorridor study (Polcorridor 2006). In this case study, opportunities for new rail freight transportation services are explored. The proposed rail services are part of intermodal transport networks, as they are linked at intermodal terminals to feeder services consisting of ferries, shipping lines, and existing shuttle trains. Because of different technical standards, changes of locomotives are needed at borders, and the planning problem thus involves multiple subsystems that need to be coordinated in addition to the coordination with neighboring systems. Asset management is thus of particular importance in this problem, as at least two fleets of locomotives have to be managed simultaneously.

The contribution of this paper is a new model formulation for *Service Network Design with Asset Management and multiple Fleet Coordination* (*SNDAM-mFC*). We model intermodal terminals and linkages between new services and existing connected services. Moreover, the need to change vehicles at borders introduces a synchronization aspect to the service network design. As far as we know, our handling of multiple fleets and fleet coordination in this setting is not addressed in the literature. We apply the new model to the Polcorridor case and find optimal design of these new services. In the computational study, we analyze the gains from further integration with the connected services, as well as the consequences of removing complicating border crossing operations.

The outline of the rest of this paper is as follows. In Section 2, we describe the planning problem. In Section 3, we present our modeling approach. The optimization model is formulated in Section 4. The computational study is presented in Section 5, while concluding remarks follow in Section 6.

1 Problem description

In this section we introduce the Polcorridor case study that motivated the model development, before describing the general planning problem in the second subsection. We finally discuss asset management issues and their effect on the representation of costs that are evaluated in the problem.

1.1 The Polcorridor study

The Polcorridor study (Polcorridor, 2006) is a large European research project set to develop new rail-based intermodal transport solutions between Northern and South-Eastern parts of Europe. The basic idea is to establish new rail freight services by utilizing previously unused railway capacity in Poland, the Czech Republic, and Austria, and create fast and reliable transport solutions that can compete with the more traditional routes through Germany. The routes through Germany are suffering from congestion, leading to long and unstable transportation times. The new rail services are part of intermodal transport networks, and they are linked at intermodal terminals to feeder services consisting of ferries, shipping lines, and existing shuttle trains. The Polcorridor project involves scientific and industrial partners in more than 10 European countries. Among the participants are rail operators that have commercial interest in the implementation of the research results. The Polcorridor geography is illustrated in Figure 1. We observe from Figure 1 that there are three major hubs: Sczcecin/Swinoujscie and Gdansk/Gdynia in Poland, and Vienna in Austria. The new rail operations will take place in the network between these hubs.

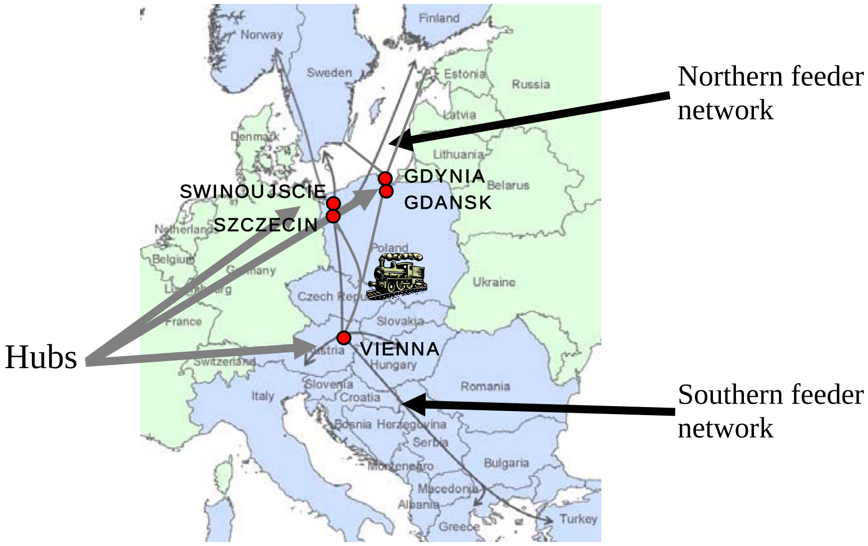


Figure 1. The Polcorridor freight supply system.

One important research issue in the Polcorridor study is *design* of the new rail operations. A strategic service network design model has been developed to give an indication of optimal service levels for these operations, including approximate frequencies (Andersen and Christiansen, 2007). The strategic model has also indicated the optimal fleet size for locomotives, and determined freight volumes that should be shipped between specific origin and destination pairs.

In this paper, we consider the problem of scheduling the new rail services in such a way that the freight in the system is transshipped as fast as possible through the intermodal network. Specific locomotive fleet sizes need to be considered in the subsystems, so the given locomotives must be utilized intelligently. There are two important aspects of this problem that we would like to highlight.

The first aspect is the integration and connection with the feeder services. The feeder services are linked to the new rail services at the intermodal hubs, and they have fixed arrival and departure times. It appears useful to incorporate information on these external services when determining the departure times of the new rail services, so that long waiting time in terminals is avoided for the freight.

The second complicating aspect of the problem is that locomotives have to be changed at the border between Poland and the Czech Republic due to different technical standards. The rail services need to cross the borders between Poland and the Czech Republic and between the Czech Republic and Austria. Two-system locomotives operate both the Austrian and the Czech networks, so changes of locomotives are not needed on the Czech/Austrian border. Unless a stock of locomotives is present at the border crossings, the locomotive changes at the Polish/Czech border introduce a synchronization problem, with one train in each direction swapping locomotives. Long waiting times for the freight might result if a locomotive from the adjacent railway system is not available when a rail service approaches the border.

1.2 General problem description

The problem we consider in this paper is designing a scheduled service network for a transportation system where several entities provide service and the exchanges and coordination with neighboring systems is critical. We refer to the services that we design as *internal* services, while the neighboring systems are referred to as *external* services. The set of internal services constitute the *internal service network* that is designed. A service is defined by its first and last stop and possible intermediate stops where flow can be loaded or unloaded. In addition to different geographical coverage, the services may have different characteristics such as speed, capacity, and priority. Each consecutive pair of terminals visited by a specific service constitute a *service leg* of that service, hence a service may have one or more service legs depending on the number of stops. Services may stop at intermediate terminals to load and unload wagons, but there are no yard classification operations taking place; we therefore do not address yard classification issues in this paper. The internal network consists of several subsystems, and these subsystems are linked at internal transfer nodes. The system is centralized in the sense that the subsystems of the internal network are treated together and the focus is on their combined performance.

Assets, wagons, cars, etc., are needed to operate services. The different subsystems require different assets, which are managed independently of other subsystems' assets. The fleets in each subsystem of the internal service network are assumed to be given and they need to cover all the services of that subsystem selected for operation. An asset may be *repositioned* between terminals if it ends a service in one location and is operating its next service from a different location.

The external services have given arrival and departure times to and from the intermodal terminals, and we assume their operations are fixed. The external services are non-homogeneous and have different loading capacities. However, since the schedules of the external services are given, flows aboard external services do not need to be explicitly represented. Volumes and arrival times for flows arriving on external services are predetermined, and can thus be represented as demand arising at the associated intermodal terminals.

There is a given demand for transportation through the network that needs to be served by the selected services. The demand is defined in terms of product volumes, each product having a specific origin and a given destination in the internal or external networks. Flows move on the selected services of the internal service network and, sometimes, on external services. Both internal and external services have limited capacities. In some cases, product loads can be transported from their origin nodes to their destination nodes using a single service. However, more complex paths with two or more services, internal or external, may be needed for other products. In the latter case, we anticipate waiting times at nodes where the flow shifts from one service to another. Moreover, it is not obvious that loads can be served immediately when they become available. These situations give rise to volumes waiting at nodes, which affect the throughput time of loads through the system.

For a given demand, the problem consists in using the given vehicle fleets to operate the selected internal services, finding the optimal frequencies of these services and their departure times, and determining the routing of the flow from origins to destinations. The overall goal is to minimize the total time of moving the demand through the system utilizing the intermodal facilities and the selected internal services. Limits on the number of departures (the *frequency*) of the internal services are assumed to be given (e.g., as output from a higher-level planning model). The problem combines the design of a scheduled service network and the management of assets available in limited quantities.

In the rest of the paper we refer to assets as vehicles and to internal transfers as border crossings. When discussing the specific Polcorridor study, we refer to the product loads as freight and to vehicles as locomotives. When discussing border crossings, the subsystems are labeled countries. For this case study all internal services are rail based.

1.3 Asset management considerations

A particularly important aspect of the problem we study is asset management. Many service network design models do not consider vehicles explicitly. The consequence may be inefficient resource utilization when vehicle assignment is carried out a posteriori. There are three reasons why asset management is particularly important for the problem we consider. First, we need to ensure that we do not plan more simultaneous operations than can be covered with the existing fleet of vehicles. Second, the cross-border operations and the synchronization requirements increase the need for clever planning of vehicle movements. Finally, the cost for acquiring locomotives is very high compared to other cost components, hence efficient resource utilization is particularly important in the rail business.

In classical fixed charge network design formulations, there are fixed costs for each design arc that is included in the design (opened), and unit costs per product flows that use the arc. In the service network design setting, opening an arc represents running a service. For our planning problem the setting is different. We assume that the design of the service network is given approximately, that is, services have been selected together with a desired frequency range. The major issue is then *how often* and *when* to run the services. We assume that there are no significant differences in service or flow-related costs relative to when services are operated. As a consequence, we do consider operating costs in the formulation. We do, however, incorporate a fixed cost for each vehicle that is used, meaning that we put a value on the ability to employ fewer vehicles than what is available. This follows from the asset management goal of operating the fleet efficiently and from the high acquisition cost of locomotives. The cost terms that are included in this problem are thus time costs for the product flows moving through the system as well as fixed costs for the vehicles that are utilized.

2 Modeling approach

In this section we describe our approach for modeling the planning problem that was presented in Section 2. The model is defined over a given *planning horizon*, typically one week or one month long. In order to capture the dynamics within the planning horizon, the planning horizon is divided into several *time periods*; these might be half an hour, one or several hours, or even one or more days. Each product has a specific time period within the planning horizon when it becomes available and can be transported towards its destination.

The internal services may leave at any time period. The departures of a given service are also denoted its *occurrences* over the planning horizon. Selecting the time periods when services depart constitutes a major decision in the optimization model. To address the scheduling aspect of the internal services, we introduce a time-space network. Each internal service has to be covered by a vehicle and in the time-space network this is represented by vehicles moving on arcs.

In the next subsections we present the physical network and the time-space representation that we use. We focus in particular on the time-space representation of the connections between internal and external services at intermodal terminals, and of the internal transfers at border crossings. We also introduce our model representation of demand and of the internal and external services. In our notation, lower-case letters are used to represent subscripts, while capital letters are used to represent data. Capital letters are also used as literal subscripts to define mnemonic composite identifiers of data. We use superscript in the variable names to indicate subcategories of variables.

2.1 Physical network

The physical network is conceptually divided into two parts, the internal and the external networks. The external network is not necessarily connected, but the union of the internal and external networks is connected. The internal and external networks are linked at the intermodal facilities.

The physical network consists of nodes representing terminals and arcs representing lines or connections. For example, the physical network for internal rail services is defined by nodes representing yards and stations, and arcs representing rail tracks.

The nodes in the network belong to one of the following mutually exclusive sets:

N_B	Set of nodes in the internal network that represent border crossings; For each border crossing, there is one node on each side of the border;
N_E	Set of nodes representing destinations of external services; These are sink nodes for freight bound for the external services;
N_{FT}	Set of flow transfer nodes at intermodal terminals; These nodes represent the connection to the external network in intermodal terminals;
N_{IM}	Set of nodes representing the internal system at intermodal terminals;
N_R	Set of nodes that are regular terminal nodes in the internal network.

The arcs in the physical network can be classified in one of the following sets:

A_s	Service legs (i, j) for internal services $s \in S$, as defined in Section 3.6;
A_f	Set of lines in the network operated by vehicles of fleet $f \in F$, as defined in Section 3.6;
A_B	Set of flow transfer arcs (i, j) at border crossings, $i, j \in N_B$;
A_E	Set of arcs (i, j) representing external services, $i \in N_{FT}, j \in N_E$;
A_I	Set of flow transfer arcs (i, j) at intermodal terminals, connecting the internal system to the flow transfer node at each terminal, $(i \in N_{IM}, j \in N_{FT}) \bigcup (i \in N_{FT}, j \in N_{IM})$.

The arc sets A_B and A_I represent connections rather than physical entities, and are thus virtual arcs. They are nonetheless included in the physical network, because the term physical network is used as opposed to time-space network, which we will define in the next subsection. Moreover, note that the external services are defined in one direction only, namely towards the external nodes N_E .

Figure 2 illustrates the operations in an intermodal terminal. The nodes representing quay are the flow transfer nodes N_{FT} as defined above, while the nodes representing the rail system belong to the set N_{IM}. The arcs between the quay and the rail nodes are flow transfer arcs belonging to the set A_I. The nodes in Figure 2 are duplicated in order to distinguish between the two directions.

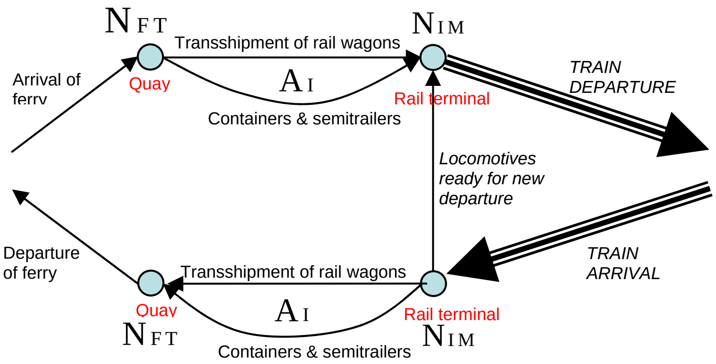


Figure 2. An intermodal terminal with transshipment between internal rail services and ferries.

Figure 2 is based on the Swinoujscie ferry terminal in the Polcorridor study, with transfers between internal rail services and external ferry services. However, the principles are similar for other modes of transportation as well. When a ferry arrives at a quay, rail wagons can be unloaded and transshipped directly to the rail terminal. Semitrailers and containers on chassis have to be hauled to the storage and loaded on piggyback wagons before train makeup in the rail terminal. The difference in handling operations is captured by different time needed for intermodal transfers, as described in Section 3.3. When trains arrive in the rail terminal, wagons are transshipped to the ferry terminal where they wait for ferries to depart. Semitrailers and containers are loaded off the piggyback wagons and moved to the storage area by the quay.

2.2 Time-space representation of the physical network

We introduce a time-space representation of the network to capture the dynamics, the time dimension of the operations. The planning horizon is divided into *time periods* $T \equiv \{1,..,T_{MAX}\}$. Each node in the physical network is replicated once for each time period considered. Arcs in the time-space network between different physical nodes represent movements of vehicles and flow, while arcs between different time representations of the same physical node represent holding of flow or vehicles. The sets of arcs in the time-space network are time-indexed versions of the arc sets defined in Section 4.1. Arc sets A_{st}, A_{ft}, A_{B_t}, and A_{I_t} are replicated in all time periods. Arc sets A_{E_t} are defined for the time periods when the external services leave the flow-transfer nodes at intermodal terminals.

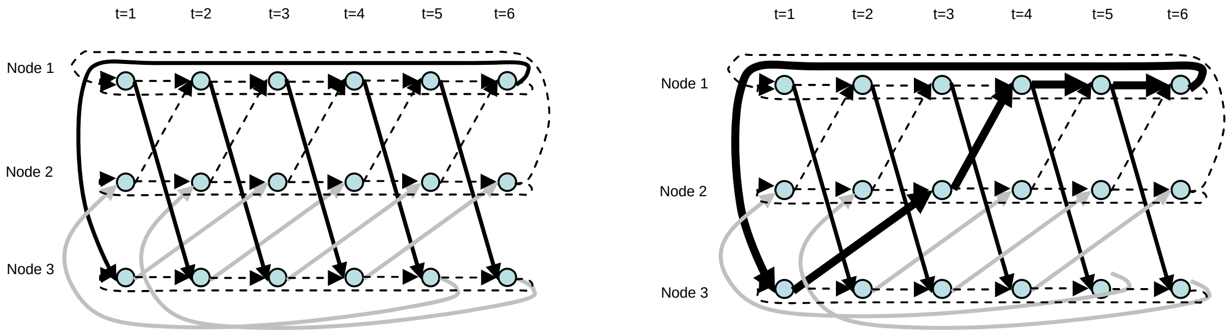
The directed graph $G = (N^T, A)$ represents the network, where N^T stands for all time realizations of the nodes N in the physical network, and A is the union of all time-indexed arc sets, $A \equiv \{(i_1, j_1),(i_2, j_2),...,(i_n, j_n)\}$, where $i \in N^T$ and $j \in N^T$, $A \subseteq N^T x N^T$.

We introduce a cyclic schedule, allowing services and flows to move from the last period to the first period of the planning horizon. The cyclic schedule represents the regularity and repetitiveness of schedules in actual operations. The service time of all services and the times needed for transportation from origin to destination of all products are shorter than or equal to the length of the planning horizon.

Services and vehicle repositioning moves are represented as paths and arcs in the time-space network. For each node, horizontal arcs between consecutive time realizations represent that product loads and vehicles are held in the same physical location from one time period to the next. Time-space representation of flow at intermodal terminals and at border crossings is discussed in Sections 3.3 and 3.4, respectively. An example of a time-space network can be found in Figure 3.

In Figure 3a), the solid lines represent services. There is one service from node 1 to node 3 (black arcs), and one service from node 3 to node 2 (grey arcs). Dotted arcs indicate repositioning moves(between different nodes and holding arcs between different time representations of same node. Repositioning might take place between any of the physical nodes, but to increase the readability, repositioning arcs are only drawn from physical node 2 to physical node 1. Vehicles may be held at any of the three physical nodes. We observe that the last period, period 6, is succeeded by the first time period. The time representation is thus cyclic.

In Figure 3b), one feasible vehicle cycle in the time-space network is illustrated. The vehicle operates the service from node 3 to node 2, starting in time period 1 and arriving in time period 3. Then, from period 3 to period 4 the vehicle is repositioned to node 1, where it is held for two time periods. In period 6 the vehicle operates the service from node 1 to node 3, arriving at time 1 where the same pattern of movements starts all over again.



3a)

3b)

Figure 3. Time-space diagram for a network with three nodes and six time periods (3a) and example of feasible service plan (3b).

2.3 Time-space representation of intermodal terminals

Regular rail terminals in the internal network are represented by one node per time period. Services arrive and depart from these nodes, and both flow and vehicles may me held there between time periods. Intermodal terminals, however, need to be represented by two nodes per time period to capture the fact that products may have different loading and unloading times. The main intermodal terminal node represents the internal system and is used for arrivals and departures of services, and vehicles may also be held “at” these nodes. The other intermodal terminal node is the flow-transfer node, where flow waits for the departing internal or external services.

When services arrive at an intermodal terminal, flow is unloaded through internal transfer arcs to the flow-transfer node. The time required for flow loading and unloading is product-dependent, representing differences between different load-carrying units. A service may transport products with different loading and unloading times. When a product has its final destination at the intermodal terminal, it leaves the network on reaching the flow-transfer node. When, on the other hand, the product's destination is an external node, the flow has to wait for departures of external services at the flow-transfer node.

As explained in Section 2.2, products delivered at the intermodal terminal by external services have their origin at the terminal, that is, at the flow-transfer node. Other products may also have their origin in the intermodal terminals and are also represented with the flow-transfer node as origin. Products bound for the internal rail services are held at the flow-transfer nodes until they can be transported by a departing service. There are loading arcs from the flow-transfer node to the intermodal terminal node.

Figure 4 illustrates an intermodal terminal connecting an internal rail system to two external nodes and external services. Solid black arcs represent internal services and holding of vehicles, while dotted black arcs represent external services. Grey arcs are flow-transfer arcs, solid and dotted arcs representing flow from and to external services, respectively. An internal service arrives at the intermodal terminal in period 3. Product A can be unloaded in one period, represented by an arc to the flow-transfer node. The external service leaves in period 4, and product A can thus leave for external node 2 with this external service. Product B becomes available at the flow-transfer node at time 4 (either from an external service or with its actual origin there). Because of the assumption that freight arriving from external services "originates" at the intermodal terminals, there are no incoming arcs from external nodes to the flow-transfer node. The internal service that product B is using does not leave until time period 9, so product B is held at the flow-transfer node until it is transferred to the intermodal terminal node at time 8, requiring one time period for loading before service departure.

At time 8, there is an arriving service with two products, C and D. Product C can be unloaded within one time period, and leaves for external node 1 with the external service at time 9. Product D has a longer unloading time, however, and misses the external service leaving at time 9. Thus, product D has to wait for the external service bound for external node 1 leaving at time 12. Product E becomes available at the flow transfer node at time 9 (either from an external service, or with its actual origin there). It has to wait until period 1 before it is loaded to the service leaving at time 3. In this small example, it is assumed that the product volumes are smaller than the capacities of the internal and external services.

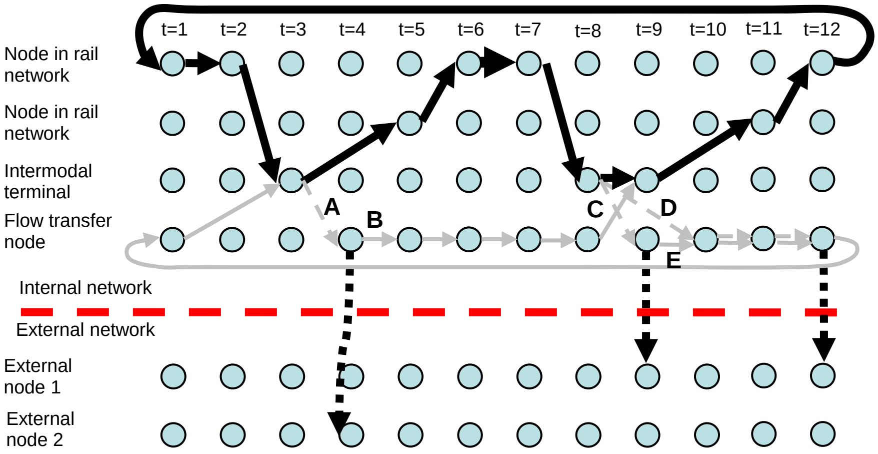


Figure 4. Time-space representation of an intermodal terminal.

2.4 Time-space representation of border crossings

Border crossings are represented by two nodes, one on each side of the border. Services arrive and depart from the border nodes on each side of the border, and artificial flow-transfer arcs ship flow between the two systems. Each such transfer has a minimum required time of one period, and a given product-dependent maximum transfer time. Vehicles may be held at the border until they are needed for new operations.

Figure 5 illustrates a time-space representation of a border crossing made up of border nodes A and B. Services arrive and depart from these nodes on each side of the border. Services are represented by solid, black arcs. Flow transfers between the two subsystems are represented by grey arcs, dotted and solid in opposite directions.

Flow-transfer arcs may cover several time periods when flow needs to wait for a locomotive for further transport. For instance, the flow arriving at the border in country B at time 4 has to wait until time 6 for further transportation. Similarly, the flow arriving at the border in country A at time 6 has to wait until time 9 for further transportation in country B. We do not allow services to be split or merged at the border crossings, so all flow arriving at the border as part of one service, constitutes a new service in the adjacent country. In Figure 5, the vehicles leave the border as part of new services immediately, the only exception being a vehicle in country A kept at the border from time 5 to time 6.

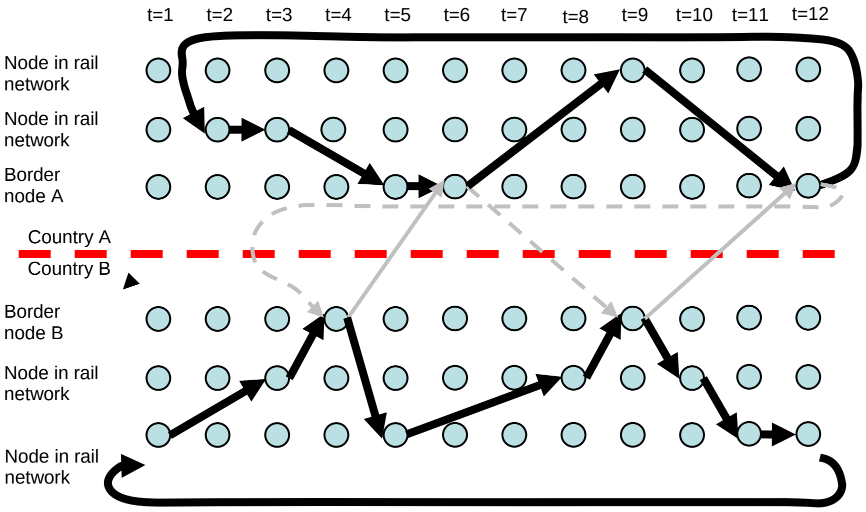


Figure 5. Time-space representation of border crossing operations.

2.5 Demand

Demand is defined in terms of products $\mathcal{P} = \{p\}$. The demand is given and all demand has to be served. Each product p belongs to a commodity group. In order to simplify the notation, commodity groups are not represented explicitly, but the commodity group influences the value of time defined below. A product $p \in \mathcal{P}$ is defined by its origin and destination terminals, O_p and D_p, respectively, where $O_p \in \mathcal{N}_{FT} \cup \mathcal{N}_R$ and $D_p \in \mathcal{N}_{FT} \cup \mathcal{N}_R \cup \mathcal{N}_E$.

Let DEM_p represent the demand volume of product *p*, measured as the number of load-carrying units, and TA_p the time when the product becomes available at its origin. For all products, we define the maximum allowed waiting time at border crossings, TBMAX_p, and the time required for intermodal handling between internal and external services, TIM_p. The latter is dependent on the type of load-carrying unit. Finally, we define the value of time, VOT_p, which is dependent on the commodity group the product belongs to. The value of time indicates how time-sensitive the product is, time-sensitive products being prioritized by the planning model.

2.6 Services

We now define the internal and external services, as well as the fleets of vehicles used in the internal service network.

2.6.1 Internal services and service network

The internal services $\mathrm{S} = \{s\}$ are defined on the network made up by intermodal terminals, border-crossing nodes, and regular terminal nodes. The service times are fixed and constant. We assume that services arrive at and leave nodes at the beginning of the time period. Each service $s \in \mathrm{S}$ is defined by its origin terminal O_s and destination terminal D_s, where $O_s, D_s \in \mathrm{N}_{\mathrm{B}} \bigcup \mathrm{N}_{\mathrm{IM}} \bigcup \mathrm{N}_{\mathrm{Ra}}$.

Let A_{st} be the set of (ordered) service legs constituting the service *s* in the time-space network. Each service leg $(i, j) \in \mathrm{A}_{st}$ represents movement between two consecutive terminals. Let T_{si} represent the departure time of service *s* from terminal i towards the next terminal. Thus, if the service leaves the origin terminal O_s at time t, it leaves node i at time $\left[(t + T_{si}) \bmod \mathit{TMAX}\right]$. We also need to define the total duration time of the service, TIME_s, as the total time between the departure from the origin terminal O_s to the arrival at destination terminal D_s, $\mathit{TIME}_s \leq \mathit{TMAX}$. The capacity of the service, defined as the number of load-carrying units, is represented by CAP_s. Finally, let parameters YL_s and YU_s be the lower and upper bounds on the number of actual departures of service *s* during the planning horizon (its frequency), respectively.

We assume that stopping, loading, and unloading times are included in the service times. Thus, services leave intermediate terminals in the same time period they arrive. Vehicles may operate new services as soon as they have arrived at a node, and flow can be transported further once it has arrived at a node. Likewise, at border crossings, we assume that a service can enter and leave the border within the same period. A more detailed representation could be considered to, for example, differentiate among various assets (e.g., locomotives and wagons). These issues are, however, beyond the scope of this paper.

2.6.2 External services

The set of external services $\mathrm{E} = \{e\}$ is only defined outbound from the intermodal terminals, starting at the flow-transfer nodes of these terminals. An external service $e \in \mathrm{E}$ is defined by its origin and destination terminals, O_e and D_e, respectively, where $O_e \in \mathcal{N}_{FT}$ and $D_e \in \mathcal{N}_E$. We also define the service capacity C_{APE_e}, and its set of departure times $\mathcal{T}_{D_e}$, $\mathcal{T}_{D_e} \subseteq \mathcal{T}$.

2.6.3 Fleets of vehicles

The number of vehicles is input from a higher-level planning model. Multiple vehicle fleets are defined to account for the need to change vehicles at border crossings. For each fleet $f \in \mathcal{F}$, we define C_{VEH_f} and V_{MAX_f}, the cost of operating a vehicle of the fleet, and the maximum number of vehicles available, respectively. We also define $\mathcal{A}_{ft}$, the set of arcs in the network operated by vehicles of that fleet, $\mathcal{A}_{ft} \subseteq (\mathcal{N}_B \bigcup \mathcal{N}_{IM} \bigcup \mathcal{N}_R) x (\mathcal{N}_B \bigcup \mathcal{N}_{IM} \bigcup \mathcal{N}_R)$, and the set $\mathcal{S}_f$ of services operated by vehicles of the fleet.

Repositioning might be needed to create feasible paths of vehicle movements. Repositioning may take place at any time through the planning horizon. The time required for repositioning from node i to node j, $(i, j) \in \mathcal{A}_{ft}$, $f \in \mathcal{F}$, is represented by $T_{R_{fij}}$.

3 Service Network Design with Asset Management and multiple Fleet Coordination (SNDAM-mFC) model

We present the SNDAM-mFC model developed for the planning problem described in Section 2, using the network representation developed in Section 3. In subsection 4.1, we introduce decision variables, while we define the objective function in subsection 4.2. Subsections 4.3-4.5 present the constraints of the model. Model solving is discussed in subsection 4.6.

3.1 Decision variables

We have two major groups of decision variables. The sets for which each decision variable is defined are presented in equations (12)-(19) of Section 4.5. The decision variables for vehicles and services are:

v_f	Number of vehicles of fleet f used;
y^H_{fit}	Number of vehicles from fleet f held at node i from time period t to the next period;
y^R_{fijt}	1, if a vehicle of fleet f is repositioned from node i at time t to node j at time $t + T_{R_{fij}}$, and 0, otherwise;.
y^S_{st}	1, if a departure of internal service s leaves its origin terminal O_s at time t, and 0, otherwise.

An *occurrence* of service s takes place when the service leaves its origin terminal at a given time t and it is represented by $y^S_{st} = 1$. The frequency of service s is then given by $\sum_t y^S_{st}$. Similarly, an *occurrence* of repositioning takes place whenever $y^R_{fijt} = 1$ for some fleet $f \in \mathcal{F}$, $(i, j) \in \mathcal{A}_{ft}$, and time $t \in \mathcal{T}$. Flow decision variables are:

x^{E}_{peijt} Volume of product p leaving an intermodal terminal's flow-transfer node i bound for external node j at time t with external service e;

x^{H}_{pit} Volume of product p held at node i from time period t to the next period;

x^{S}_{psijt} Volume of product p leaving terminal i for terminal j with internal service s at time t;

x^{T}_{pitju} Volume of product p transferred between border nodes i and j from time t to time u, or loaded/unloaded at an intermodal terminal, from time t to time u.

3.2 Objective function

$$Min\left[\begin{array}{l}\sum_{p\in\mathrm{P}}\ \sum_{i\in\mathrm{N_{FT}}\cup\mathrm{N_R}}\ \sum_{t\in\mathrm{T}} VOT_p x^{H}_{pit} + \sum_{p\in\mathrm{P}}\sum_{s\in\mathrm{S}}\ \sum_{(i,j)\in\mathrm{A}_{st}}\ \sum_{t\in\mathrm{T}} VOT_p (T_{sj}-T_{si}) x^{S}_{psijt} + \\ \sum_{p\in\mathrm{P}}\ \sum_{(i,j)\in\mathrm{A_{B_t}}\cup\mathrm{A_{I_t}}}\ \sum_{t\in\mathrm{T}}\sum_{u\in\mathrm{T}} VOT_p (u-t) x^{T}_{pijtu} + \sum_{f\in\mathrm{F}} CVEH_f v_f\end{array}\right] \qquad (1)$$

The objective function (1) minimizes the total "fixed" cost of the fleets plus the sum of the product flow waiting and transportation times weighted by the corresponding product value of time. As indicated in the problem statement, the flow costs on external services are not included, because the transportation operations on these systems are not within the scope of the present planning optimization process.

3.3 Constraints for services and vehicle movements

$$\begin{array}{l}\sum_{s\in\mathrm{S}_f}\ \sum_{\substack{u\in\mathrm{T}:u\le t\\ u+TIME_s>t>\ :}} y^{S}_{su} + \sum_{s\in\mathrm{S}_f}\ \sum_{\substack{u\in\mathrm{T}:u>t\\ (u+TIME_s)\bmod TMAX>t}} y^{S}_{su} + \\ \sum_{(i,j)\in\mathrm{A}_{ft}}\ \sum_{\substack{u\in\mathrm{T}:u\le t\\ u+TR_{fij}>t>\ :}} y^{R}_{fiju} + \sum_{(i,j)\in\mathrm{A}_{ft}}\ \sum_{\substack{u\in\mathrm{T}:u>t\\ (u+TR_{fij})\bmod TMAX>t:}} y^{R}_{fiju} + \qquad \forall f\in\mathrm{F}, t\in\mathrm{T}v, \\ \sum_{i\in\mathrm{N}\setminus\mathrm{N_E}\cup\mathrm{N_{FT}}:} y^{H}_{fit} - v_f \le 0,\end{array} \qquad (2)$$

$$\begin{aligned}&\sum_{s\in \mathrm{S}_f:O_s=i} y^S_{st} - \sum_{s\in \mathrm{S}_f:D_s=i}\ \sum_{u\in \mathrm{T}:[(u+TIME_s)\bmod T_{MAX}]=t:} y^S_{su} + \\ &\sum_{j\in \mathrm{N}:(i,j)\in \mathrm{A}_{ft}:} y^R_{fijt} - \sum_{j\in \mathrm{N}:(j,i)\in \mathrm{A}_{ft}}\ \sum_{u\in \mathrm{T}:[(u+TR_{fji})\bmod T_{MAX}]=t} y^R_{fjiu} + \\ &y^H_{fit} - y^H_{fi(t-1)|t>1} - y^H_{fiT_{MAX}|t=1} = 0\ ,\end{aligned} \qquad \begin{aligned}&\forall f\in \mathrm{F}, i\in \mathrm{N}_B \bigcup \mathrm{N}_{IM} \bigcup \mathrm{N}_R, \\ &t\in \mathrm{T}\ ,\end{aligned} \qquad (3)$$

$$YL_s \le \sum_{t\in \mathrm{T}} y^S_{st} \le YU_s\ , \qquad \forall s\in \mathrm{S}. \qquad (4)$$

Constraints (2) ensure that in each time period, the available vehicles cover the services and the repositioning activities taking place simultaneously. Equations (3) ensure vehicle balance for all services, repositioning, and holding activities at all nodes. Services are accounted for at their origin and destination terminals, only, because a service arrival and departure are balanced at all intermediate nodes. Finally, constraints (4) ensure that all service frequencies are within the required intervals.

3.4 Constraints restricting flow

Constraints (5)-(11) restrict flow values on internal and external services, as well as waiting at terminals. Flow capacities on internal service legs and external services are enforced through constraints (5) and (6), respectively.

$$\sum_{p\in \mathrm{P}_s} x^S_{psijt} - \sum_{u\in \mathrm{T}:u=(T_{MAX}+t-T_{si})\bmod T_{MAX}\,\mathrm{s}} CAP_s\, y^S_{su} \le 0\,, \qquad \forall s\in \mathrm{S}, (i,j)\in \mathrm{A}_{st}, t\in \mathrm{T}\ , \qquad (5)$$

$$\sum_{p\in \mathrm{P}_f} x^E_{peO_eD_et} \le CAPE_e\,, \qquad \forall e\in \mathrm{E}, t\in \mathrm{T}_{D_e}. \qquad (6)$$

Constraints (7)-(11) enforce node balance for flows according to the node type. Flow balance constraints for border crossings and the internal system at intermodal terminals are found in (7). These constraints balance flows arriving and leaving on services with transfer arcs to and from border nodes at border crossings and flow-transfer nodes at intermodal terminals, respectively. Flow balance for regular terminals in the internal network is provided through constraints (8). Flow can be held at these nodes from one period to the next, the incremental change in the flow volumes held being the difference between incoming and outgoing flows within the period. For transfer nodes, constraints (9) define similar volumes of flows held and balance flows toward external services with flows from and to the internal part of the corresponding intermodal terminal.

$$\begin{aligned}&\sum_{s\in \mathrm{S}}\sum_{j\in \mathrm{N}} x^{S}_{psijt} - \sum_{s\in \mathrm{S}}\sum_{j\in \mathrm{N}} \sum_{u\in \mathrm{T}:\left[(u+T_{sj}-T_{si}) \bmod T_{MAX}\right]=t} x^{S}_{psjiu} + \\ &\sum_{j\in \mathrm{N}}\sum_{u\in \mathrm{T}} x^{T}_{pijtu} - \sum_{j\in \mathrm{N}}\sum_{u\in \mathrm{T}} x^{T}_{pjiut} = 0 \qquad ,\end{aligned} \qquad \forall p\in \mathrm{P}, i\in \mathrm{N}_{B}\bigcup \mathrm{N}_{IM}, t\in \mathrm{T}; \tag{7}$$

$$\begin{aligned}&\sum_{s\in \mathrm{S}}\sum_{j\in \mathrm{N}} x^{S}_{psijt} - \sum_{s\in \mathrm{S}}\sum_{j\in \mathrm{N}} \sum_{u\in \mathrm{T}:\left[(u+T_{sj}-T_{si}) \bmod T_{MAX}\right]=t} x^{S}_{psjiu} + \\ &x^{H}_{pit} - x^{H}_{pi(t-1)|t>1} - x^{H}_{piT_{MAX}|t=1} = \begin{cases} DEM_{P}, & i = O_p \text{ and } t = TA_p \\ 0, & otherwise \end{cases} \quad ,\end{aligned} \qquad \forall p\in \mathrm{P}, i\in \mathrm{N}_{R} : i \neq D_p, t\in \mathrm{T}; \tag{8}$$

$$\begin{aligned}&\sum_{j\in \mathrm{N}}\sum_{u\in \mathrm{T}} x^{T}_{pijtu} + \sum_{e\in \mathrm{E}}\sum_{j\in \mathrm{N}} x^{E}_{peijt} - \sum_{j\in \mathrm{N}}\sum_{u\in \mathrm{T}} x^{T}_{pjiut} + \\ &x^{H}_{pit} - x^{H}_{pi(t-1)|t>1} - x^{H}_{piT_{MAX}|t=1} = \begin{cases} DEM_{P}, & i = O_p \text{ and } t = TA_p \\ 0, & otherwise \end{cases} \quad ,\end{aligned} \qquad \forall p\in \mathrm{P}, i\in \mathrm{N}_{FT} : i \neq D_p, t\in \mathrm{T}. \tag{9}$$

Constraints (10) balance flows at the product destination nodes. They state that, for regular nodes as well as for freight transfer nodes at intermodal terminals that are product destination nodes, the total inbound flow has to equal the demand of the corresponding product. Equations (11) enforce the same principle for external nodes.

$$\sum_{s\in \mathrm{S}}\sum_{j\in \mathrm{N}}\sum_{t\in \mathrm{T}} x^{S}_{psjit} + \sum_{j\in \mathrm{N}}\sum_{t\in \mathrm{T}}\sum_{u\in \mathrm{T}} x^{T}_{pjitu} = DEM_{p}, \qquad \forall p\in \mathrm{P}, i\in \mathrm{N}_{FT}\bigcup \mathrm{N}_{R} : i = D_p, \tag{10}$$

$$\sum_{e\in \mathrm{E}}\sum_{j\in \mathrm{N}_{IM}}\sum_{t\in \mathrm{T}} x^{E}_{peijt} = \begin{cases} DEM_{p}, & i = D_p \\ 0, & otherwise, \end{cases} \qquad \forall p\in \mathrm{P}, i\in \mathrm{N}_{E}. \tag{11}$$

3.5 Non-negativity and integrality requirements

$$x^{E}_{peijt} \geq 0, \qquad \forall p \in \mathrm{P}, e \in \mathrm{E}, (i,j) \in \mathrm{A}_{\mathrm{E}_{t}}, t \in \mathrm{T}_{\bar{D}_e}, \tag{12}$$

$$x^{H}_{pit} \geq 0, \qquad \begin{array}{l} \forall p \in \mathrm{P}, i \in \mathrm{N}_{\mathrm{FT}} \cup \mathrm{N}_{\mathrm{R}} : i \neq D_p, \\ t \in \mathrm{T} \setminus ([T_{A_p} + T_{MAX} - 1] \bmod T_{MAX}), \end{array} \tag{13}$$

$$x^{S}_{psijt} \geq 0, \qquad \begin{array}{l} \forall p \in \mathrm{P}, s \in \mathrm{S}, (i,j) \in \mathrm{A}_{S_{st}}, \\ t \in \mathrm{T}: \setminus \left\{ t : (t < T_{A_p})\, and\ (t + T_{sj} - T_{si} \geq T_{A_p}) \right\}, \end{array} \tag{14}$$

$$x^{T}_{pijtu} \geq 0, \qquad \begin{array}{l} \forall p \in \mathrm{P}, (i,j) \in \mathrm{A}_{\mathrm{I}_t}, t \in \mathrm{T}, u \in \mathrm{T} : u = t + T_{IM_p} \setminus \\ \left\{ t,u : (t < T_{A_p})\, and\ (u \geq T_{A_p}) \right\} \cup \\ p \in \mathrm{P}, (i,j) \in \mathrm{A}_{\mathrm{B}_t}, t \in \mathrm{T}, u \in \mathrm{T} : u = \left\{ t+1, .., t + T_{BMAX_p} \right\} \setminus \\ \left\{ t,u : (t < T_{A_p})\, and\ (u \geq T_{A_p}) \right\} \qquad , \end{array} \tag{15}$$

$$v_f \in \left\{ 0, .., V_{MAX_f} \right\}, \qquad \forall f \in \mathrm{F}, \tag{16}$$

$$y^{H}_{fit} \in \left\{ 0, .., V_{MAX_f} \right\}, \qquad \forall f \in \mathrm{F}, i \in \mathrm{N} \setminus (\mathrm{N}_{\mathrm{Ea}} \cup \mathrm{N}_{\mathrm{FTa}}), t \in \mathrm{T}, \tag{17}$$

$$y^{S}_{st} \in \{0,1\}, \qquad \forall s \in \mathrm{S}, t \in \mathrm{T}, \tag{18}$$

$$y^{R}_{fijt} \in \{0,1\}, \qquad \forall f \in \mathrm{F}, (i,j) \in \mathrm{A}_{ft}, t \in \mathrm{T}. \tag{19}$$

All flow variables are non-negative and continuous. The initial volumes waiting at terminals x^{H}_{pit} are, by definition, 0 at all the time periods before a product becomes available. We have therefore removed x^{H}_{pit} from the model formulation for $t = [(T_{A_p} + T_{MAX} - 1) \bmod T_{MAX}]$. This is compatible with the requirement that a product has to be transported from its origin to its destination within the planning horizon.

The number of vehicles in use, v_f, and the number of vehicles held at nodes, y^{H}_{fit}, are integer variables bounded by number of available vehicles of the respective fleet type. Finally, decision variables for service departures, y^{S}_{st}, and repositioning moves, y^{R}_{fijt}, are binary variables.

3.6 Solving the model

Magnanti and Wong (1984) show that the uncapacitated fixed charge network design problem is NP-hard. As the capacitated version is even harder (Balakrishnan et al., 1997), this problem also belongs to the class of NP-hard problems. The introduction of design balance constraints on the nodes further complicates the model, as does the explicit representation of vehicles. Only smaller instances can thus be solved to optimality with exact methods. For our case study, we are able to solve the model to optimality, as described in Section 5.2.

4 Computational study

The experimental phase of our study aimed to observe the behavior of the model proposed and to analyze the impact of possible modifications in external (external services schedules) and internal (border crossings) policies.

In Section 5.1, we briefly present the data used, based on the application presented initially. Section 5.2 discusses the implementation of the model. In Section 5.3, we define the scenarios used to analyze possible policy changes. Results are presented and analyzed in Section 5.4.

4.1 Experimental data

Figure 6 illustrates the internal and external networks for the Polcorridor network presented in Figure 1. Links in the internal and external networks are solid and dotted, respectively. The internal network is made up of the railway system between the three intermodal hubs in Figure 6. The new services that are designed operate in this internal network. On the border crossings between Poland and the Czech Republic, differences in signaling systems require changes of locomotives.

The internal service network consists of 22 services, for which the model determines the departure times. The physical network consists of 17 nodes, including six external nodes representing destinations of the external services. In total, there are 44 departures of external services throughout the planning horizon. The network contains three intermodal terminals and two border crossings. There are 84 time periods for a planning horizon of one week with time periods of two hours. Transportation times, handling times, and departure times of external services have been collected through the Polcorridor project.

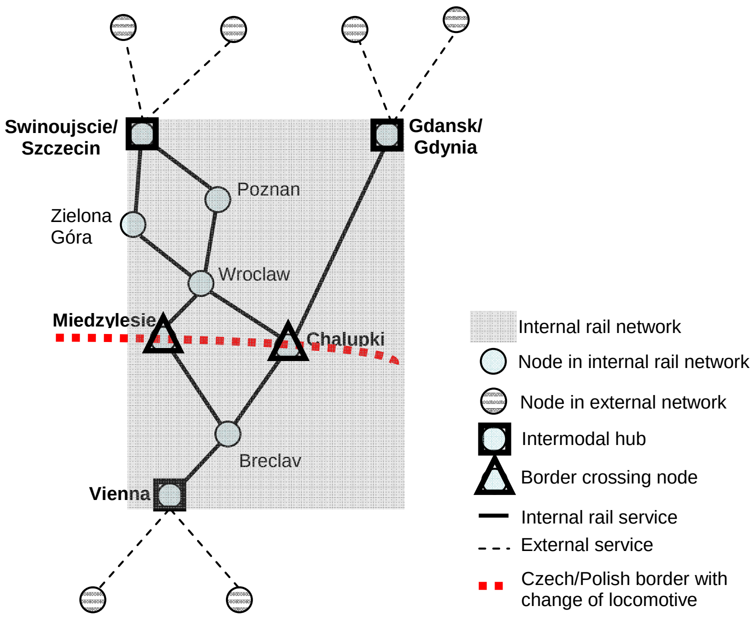


Figure 6. The Polcorridor network with the internal railway network connected to external services in intermodal hubs.

Demand data was originally extracted from external trade statistics, with freight volumes in tons at month level. The demand has been recalculated to measures in numbers of load carrying units at week level. The model described in this paper accounts for the time-related system dynamics. It was thus necessary to “disperse” the demand throughout the planning horizon. Demand was divided into clusters representing arrivals of ferries and other external services to intermodal terminals. In addition, a random number generator based on a uniform distribution has been used to represent more accidental demand that arises throughout the planning horizon, but which is not delivered by external services. The demand consists of 40 products.

The lower and upper bounds on service frequencies were rather loose in our application, because these bounds were determined through scenario runs at a higher-level planning model. We were however able to add lower and upper bounds on clusters of services. For instance, we imposed lower and upper bounds on the total number of services between Szczecin/Swinoujscie and Vienna that stop in Wroclaw, without considering the physical routes used.

4.2 Model implementation

The model (1)-(19) was implemented in XPRESS-IVE version 1.16.20 and run on a computer with a Pentium 4, 3Ghz processor with 1 GB memory. The LP-relaxation is weak and the model converges slowly. We found an integer solution after a few hours of running time, but no new integer solutions were found within 24 hours of running time. The optimality gap was still more than 10.4% after 24 hours of running time, and it had improved by only 0,1% during the last 20 hours.

We introduce therefore two types of constraints in order to strengthen the relaxation and speed up the solution process. Strong forcing constraints on the freight flows are introduced in (20). For capacitated multicommodity network design without design balance constraints, the strong forcing constraints yield a significantly stronger LP-relaxation (Chouman *et al.*, 2003) and similar results were obtained for our case as well.

$$x_{psijt}^{S} - \sum_{u \in \mathrm{T} : u = (T_{MAX} + t - T_{si}) \bmod T_{MAX}\, \mathrm{s}} DEM_{p}\, y_{su}^{S} \le 0\,, \qquad \forall p \in \mathrm{P}\,, s \in \mathrm{S}\,, (i, j) \in \mathrm{A}_{st}\,, t \in \mathrm{T}\,. \tag{20}$$

Secondly, we reduce the large number of transfer arcs by introducing forcing constraints on the border transfer arcs. From the representation of border crossings in Figure 5, we observe that transfer arcs at borders are only needed for the time periods where there is an arriving service. This property is defined in constraints (21):

$$\sum_{u \in \mathrm{Ts}} x_{pijtu}^{T} - \sum_{u \in \mathrm{T} : [(T_{MAX} + u + TIME_{jis}) \bmod T_{MAX}] = t\, \mathrm{s}} x_{psjiu}^{S} \le 0\,, \qquad \forall p \in \mathrm{P}\,, s \in \mathrm{S}\,, (i, j) \in \mathrm{A}_{st}\,, t \in \mathrm{T}\,. \tag{21}$$

We also removed some border transfer arcs initially by using the following idea. For a product that has its origin in one country and its destination in another country, we may remove transfer arcs at borders directed towards the product's origin country. Moreover, we performed some problem-specific reductions in the number of transfer arcs at intermodal terminals based on the exploration of the origin and destination nodes for these products. For instance, a product which has its origin or destination in Gdansk/Gdynia, will never be transferred through the Szczecin/Swinoujscie terminal.

Finally, we added single-arc cutset inequalities in line with the description in Chouman *et al.* (2003). These valid inequalities strengthen the linear relaxation, but we were not able to find inequalities that significantly affected the running times of the MIP-problem.

By implementing all the ideas discussed in this subsection, the model had 3530 integer design variables, 77500 continuous flow variables and 678000 constraints. The model was then solved to optimality in about 12 hours of processing time. In particular, the strong forcing constraints (20) reduced the solution time considerably. As this model is not intended to be solved on a daily basis, there is no need to work on further reducing the running times at this stage. For more complex networks, either from increased number of nodes in the physical network or from increased number of time periods, decomposition or heuristic approaches should be used.

4.3 Model scenarios

We run the model with four different scenarios. The scenarios are used to analyze the effect of integration with external services and the effect of border crossing operations. Indeed, the latter could be removed as the result of improved technology or harmonization of technical and legal standards.

4.3.1 Baseline scenario

In the baseline scenario, model (1)-(21) is run as it is, resulting in an optimal set of operations for the existing design problem. This scenario represents the current situation, without any changes in border crossing operations, and without changing the departure times of the external services.

4.3.2 External integration

The external integration scenario is used to analyze the potential of greater integration with external services. If we allow the model to determine the departure times of the external services as well, the internal and external services will be fully integrated. Such an extreme solution would not be realistic in the current context of the real-world planning problem. Nevertheless, it would be interesting to evaluate the order of magnitude of the gain resulting from such integration, and it could emphasize the importance of this issue.

For this scenario, we introduce new decision variables y_{et}^{E}, which equal 1 if an occurrence of external service e leaves its origin terminal at time t, and 0, otherwise. To enforce operating practice of the external service provider, we also introduce Y_e^E , the departure frequency of external service e through the planning horizon. We then replace constraints (6) with constraints (6b) and add constraints (22) enforcing that the departure frequency determined by the model for each external service equals the given frequency Y_e^E The sets T_{D_e}, representing the departure times of the external services in the baseline scenario, are not needed in the external integration scenario.

$$\sum_{p \in \mathrm{P}f} x_{peO_eD_et}^{E} - CAPE_e y_{et}^{E} \leq 0 , \qquad \forall e \in \mathrm{E}, t \in \mathrm{T} \tag{6b}$$

$$\sum_{t \in \mathrm{T}} y_{et}^{E} = Y_e^E , \qquad \forall e \in \mathrm{E}. \tag{22}$$

4.3.3 Internal integration

In the internal integration scenario, we analyze the impact of border-crossing operations. We perform this analysis by removing the border crossing operations completely. This implies that there is no more waiting time at borders, and that one fleet of vehicles is sufficient to carry out the operations. The results of this scenario will give indications on the loss in efficiency currently incurred due to the non-integrated European rail networks.

This scenario implies that the fleet index, f, is removed from all data, variables and constraints. The maximum number of vehicles of each fleet, $VMAX_f$, are merged to an overall maximum number of vehicles, $VMAX$. Moreover, all border crossing nodes are changed to regular terminal nodes, and the flow-transfer arcs are only defined at intermodal terminals, as there are no freight transfers at borders.

4.3.4 Full integration

The fourth scenario combines the ideas of the external and internal integration, and is labeled “full integration”. In this scenario, we remove the need for vehicle changes at borders and allow the model to determine the departure times of the external services. This means that the model changes described in Sections 5.3.2 and 5.3.3 are introduced simultaneously.

4.4 Results

In this section we present results from model run with the scenarios defined in Section 5.3. In Table 1 we present components of the time cost measure based on the objective function of the model, while in Figure 7, we present the share of the total time spent on the different activities within each scenario.

Table 1. Time costs arising from different components of the model's objective function in each scenario.

Time cost component	Baseline scenario	External integration	Internal integration	Full integration
Time on internal services	70.4	69.7	69.3	69.5
Waiting at borders	4.4	5.1	0.0	0.0
Waiting in intermodal terminals	36.3	15.5	39.3	17.1
Waiting at other terminals	1.3	1.7	1.2	2.5
Loading/unloading in intermodal terminals	14.2	14.2	14.2	14.2
Total time costs in objective function	126.7	106.0	124.1	103.3

In Table 1, we observe that all integration scenarios have lower total time costs than the baseline scenario. This is expected, because both internal and external integration scenarios relax the model. In the baseline scenario, the major components are time on internal services, waiting time at intermodal terminals, and loading/unloading at intermodal terminals. The latter term is equal in all scenarios, because the loading and unloading times are constant and given.

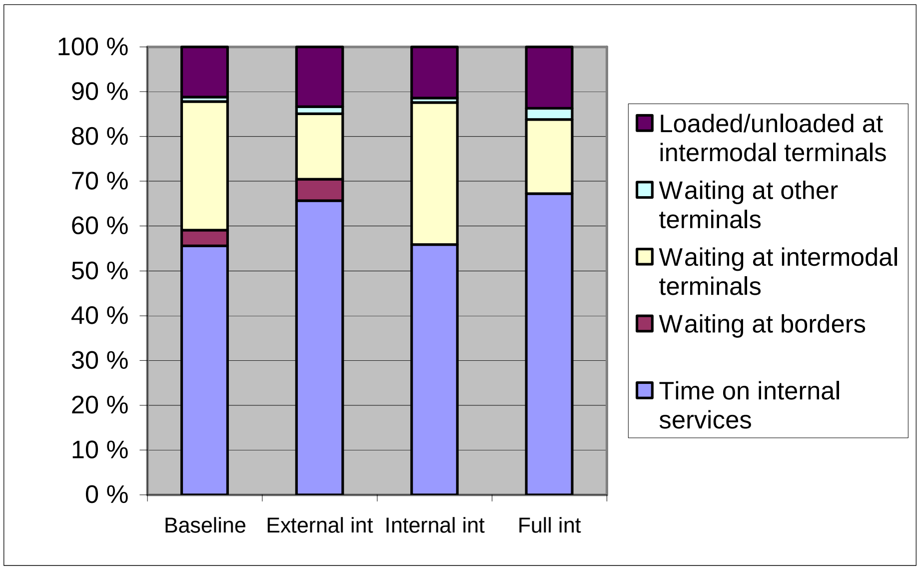


Figure 7. Share of time spent on the different activities for the flow in the various scenarios.

The external integration scenario reduces the waiting time at intermodal terminals significantly, as can be seen from Table 1 and Figure 7. However, because the number of departures of the external services is limited, some waiting time must be anticipated at the intermodal terminals. Moreover, we observe that the waiting time at borders increases slightly in this scenario. In the internal integration scenario, waiting at borders is removed, but waiting at intermodal terminals increases compared to the baseline scenario. In the full integration scenario, the total benefit of internal and external integration is somewhat lower than in the individual integration scenarios. We observe that the waiting time at intermodal terminals is not reduced as much as in the external integration scenario.

An interesting observation from the results in Table 1 is that the benefit from internal integration is significantly smaller than the benefit from external integration. While the total time costs decrease by more than 18% in the external integration scenario, the costs savings is around 2% in the internal integration scenario. One reason for this difference is that the costs associated with waiting time at intermodal terminals were defined initially significantly larger than for border crossings.

In Table 2, we present key figures related to services and vehicles for the four scenarios. We observe that the operations have strong similarities throughout the scenarios. The number of vehicles and the number of services operated are almost the same in all scenarios. This is in line with our expectations, because the demand is the same in all scenarios. However, the baseline and external integration scenarios have one more weekly northbound departure than the two other scenarios. The number of service departures in each scenario is further illustrated in Figure 8. Note that the services described in Table 2 consist of two services in Figure 8 – one in Poland and one in the Czech Republic and Austria.

Table 2. Key figures related to services and vehicle usage.

	Baseline scenario	External integration	Internal integration	Full integration
No of vehicles in use	6	6	6	6
No of southbound/ northbound service departures per week	10 / 11	10 / 11	10 / 10	10 / 10
Operating hours services (no of time periods)	392	389	380	370
Operating hours repositioning (no of time periods)	29	47	26	0
Vehicles held at nodes (no of time periods)	83	68	98	134

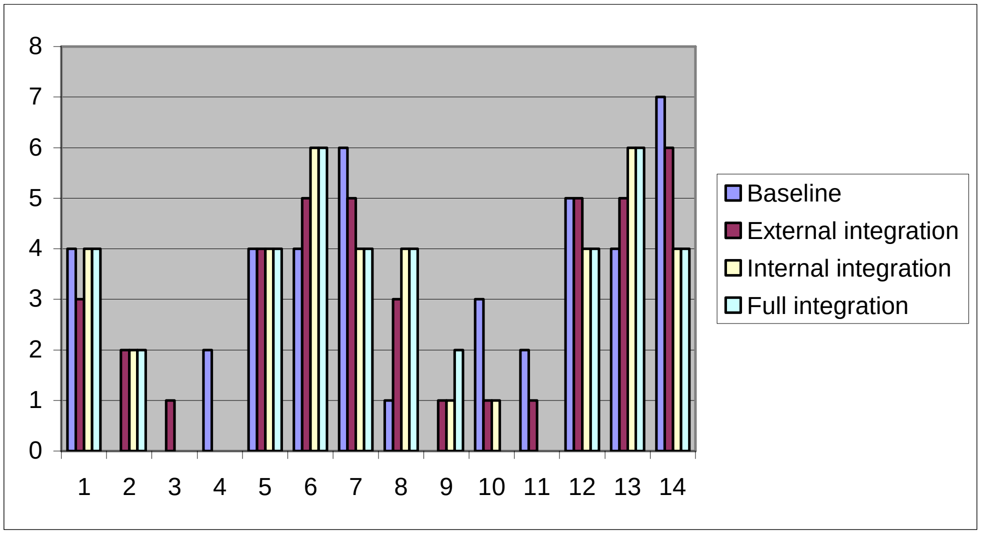


Figure 8. Number of occurrences of each service in the various scenarios for the 14 out of 22 services that were selected for operation in at least one scenario.

The removal of border crossing procedures in the internal- and full integration scenarios could have implied a reduced number of vehicles requested. However, this depends on how much the vehicles were used in the baseline scenario. If the vehicles were not heavily used in the baseline scenario, we could have saved some when integrating the two networks. We observe from Table 2 that the internal and full integrations scenarios have the largest idle times of vehicles, which is a measure of idle time. We also illustrate this in Figure 9, where we present an illustration of the utilization of the vehicles in each scenario. The white spaces in Figure 9 represent idle vehicle times, which clearly are most conspicuous in the full integration scenario.

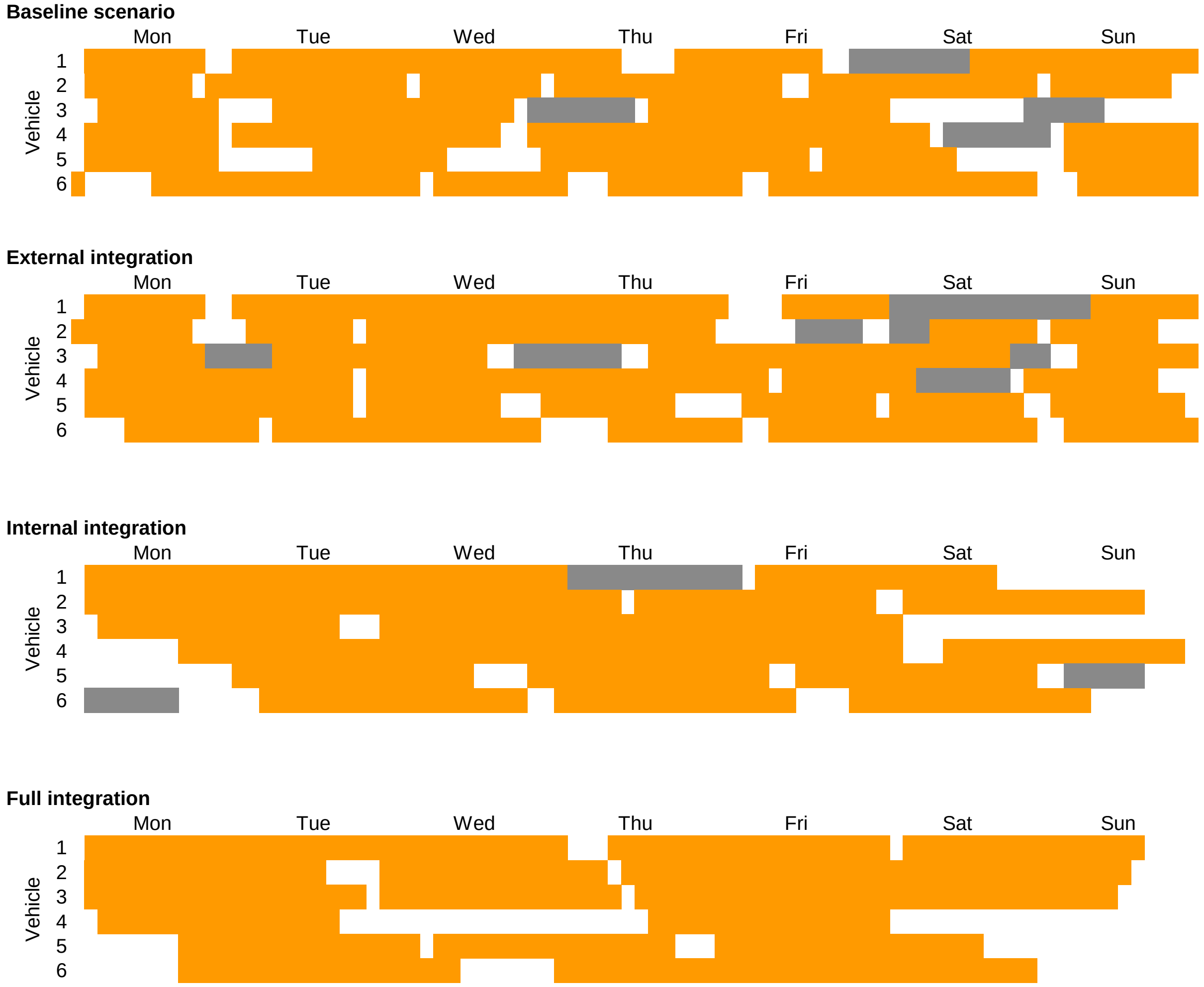


Figure 9. Utilization of vehicles throughout the planning horizon in the various scenarios. Shaded cells indicate that the vehicle is operating services, while cells with vertical lines indicate repositioning of vehicle, and white spaces indicate that the vehicle is idle waiting at nodes.

5 Concluding remarks

In this paper, we have developed a model class for *Service Network Design with Asset Management and multiple Fleet Coordination* (SNDAM-mFC). The model is an extension of the design-balanced fixed charge network design model, as described in Pedersen *et al*. (2007). These formulations arise naturally in the design of transportation services but, nevertheless, few attempts have been made to include the design balance aspect explicitly in service network design. Moreover, the model introduces fleet sizing consideration into the design, and handles multiple fleets, which is needed for cross-border analysis where changes of vehicles are required. The requirements for changes of vehicles at borders introduce an interesting synchronization issue at borders. Finally, the model handles interaction between services being designed and services in collaborating transportation systems. This feature is particularly interesting for intermodal transportation.

In the computational study, we have analyzed a case where opportunities for new rail freight services are explored. We have found the optimal service network and evaluated the possible contribution from full synchronization between the internal and external services. We have also analyzed the potential from the integration of the two railway systems where the new services are designed, which would be the case if border crossing operations could be removed. The largest potential was found from synchronization with external services, as the time costs were significantly reduced when we allowed the model to determine departure times of external services. This suggests a strong focus on such synchronization. Former analyses of Eastern European railroads have pointed to low train speed issues. Our analysis suggests that even without improving the running speed of trains, a lot can be achieved from efficient intermodal and intramodal synchronization. Increased train speed usually depends on huge investments in improved infrastructure and might require a long time for implementation. In the short run, operators should thus focus on synchronization with other operators. This result suggests a focus on collaboration and building strategic alliances.

While these results apply to the actual case study only, they also indicate the interest of a comprehensive formulation in addressing such complex issues. Applying the model to other planning problems would be interesting in order to analyze whether the results obtained for the Polcorridor study may be valid in other contexts as well. The results also point to the need for further studies of design and operation of systems involving multiple fleet cooperation and synchronization, in particular in the context of intermodal transport solutions.

From the analysis of reduced border crossing operations, we identified a smaller potential for improved performance of the transportation services. On the one hand, one could claim that the border crossing operations with changes of vehicles is not a major obstacle to efficient and competitive operations. On the other hand, however, the impact of border crossings on the transportation time variability was not explicitly addressed.. Thus, for example, we did not explicitly consider the impact of missing vehicles on one side of the border when a service arrives on the other side. The scenarios focusing on the coordination with external systems have shown, however, that such missed connections would have a significant impact. Thus, the insights gained thought the present study are valuable in initiating further studies, particularly as part of developing disruption-management solutions,

The model presented in this paper was inspired by the Polcorridor case study. Consequently, some aspects may not apply to other planning problems, while issues have not been included. We believe, however, that the modeling framework and the main ideas we propose lay the ground work for more comprehensive studies in this area. The insights relative to the asset management issues, as well as to those relative to the coordination and synchronization of services among collaborating transportation systems are particularly important and relevant in this context.

The computational difficulty associated to addressing capacitated network design problems in general, and the model proposed in this paper in particular, also point to the continuing need for additional work on developing efficient solution methods for these formulations. Column generation-based implicit enumeration methods and metaheuristics appear the most promising. We hope to report on such developments in the near future.

Acknowledgements

This work has received financial support from The Norwegian Research Council through the Polcorridor Logchain project. Partial funding has also been made available from the Natural Sciences and Engineering Research Council of Canada through its Discovery and Industrial Research Chair grant programs. We want to thank two anonymous referees for valuable comments that have improved the presentation of the paper.

References

Andersen J, Christiansen M 2007. Optimal design of new rail freight services. Working paper, Norwegian University of Science and Technology.

Balakrishnan A, Magnanti TL , Mirchandani P 1997. Network Design. In: Dell'Amico M, Maffoli F, Martello S (eds), Annotated bibliographies in combinatorial optimization. John Wiley & Sons: New York, NY;1997. p. 311-334.

Chouman M, Crainic TG, Gendron B 2003. A cutting-plane algorithm based on cutset inequalities for multicommodity capacitated fixed charge network design. Publication CRT-2003-16, Centre de recherche sur les transports, Université de Montréal.

Crainic TG. Service network design in freight transportation. European Journal of Operational Research 2000; 122(2); 272-288.

Crainic TG, Ferland J-A, Rousseau J-M. A tactical planning model for rail freight transportation. Transportation Science 1984; 18 (2); 165-184.

Crainic TG, Kim KH 2007. Intermodal transportation. In: Barnhart C, Laporte G (eds), Handbooks in Operations Research and Management Science, vol. 14. Chapter 8; 467-537.

Crainic TG, Rousseau J-M. Multimode, multicommodity freight transportation: A general modeling and algorithmic framework for the service network design problem, Transportation Research B 1986; 20(3); 225-242.

Dall'Orto LC, Crainic TG, Leal JE, Powell WB. The single-node dynamic service scheduling and dispatching problem. European Journal of Operational Research 2006; 170(1); 1-23.

European Commission 2001. White paper: European transport policy for 2010: Time to decide.

Farvolden JM, Powell WB. Subgradient methods for the service network design problem. Transportation Science 1994; 28 (3); 256-272.

Gorman GF. An application of genetic and tabu searches to the freight railroad operating plan problem. Annals of Operations Research 1998; 78; 51-69.

Keaton MH. Designing optimal railroad operating plans: Lagrangian relaxation and heuristic approaches. Transportation Research Part B: Methodological 1989; 23(6); 415-431.

Keaton MH. Service-cost tradeoffs for carload freight traffic in the U.S. rail industry. Transportation Research Part A: Policy and Practice 1991; 25(6); 363-374.

Keaton MH. Designing optimal railroad operating plans: A dual adjustment method for implementing Lagrangian Relaxation. Transportation Science 1992; 26; 263-279.

Lai MF, Lo HK. Ferry service network design: optimal fleet size, routing and scheduling. Transportation Research Part A: Policy and Practice 2004; 38; 305-328.

Lium A-G, Crainic TG, Wallace SW 2006. Stochastic service network design: The importance of taking uncertainty into account. Working paper, Molde University College, Norway.

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

Magnanti TL, Wong RT. Network design and transportation planning: models and algorithms. Transportation Science 1984; 18(1); 1-55.

Pedersen, MB. Optimization models and solution methods for intermodal transportation. PhD thesis, Centre for Traffic and Transport, Technical University of Denmark, 2006.

Pedersen MB, Crainic TG. Optimization of intermodal freight train service schedules on train canals. Publication, Centre de recherche sur les transports, Université de Montréal, 2007.

Pedersen MB, Crainic TG, Madsen OBG. Models and tabu search meta-heuristics for service network design with asset-balance requirements. Publication, Centre de recherche sur les transports, Université de Montréal, 2007.

Polcorridor 2006. Project description. http://www.eureka.be/inaction/AcShowProject.do?id=2727. October 2006.

Smilowitz KR, Atamtürk A, Daganzo CF. Deferred item and vehicle routing within integrated networks. Transportation Research Part E: Logistics and Transportation 39: 305-323, 2003.