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Intermodal freight transport planning – A receding horizon control approach

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Abstract

This paper investigates intermodal freight transport planning problems among deep-sea terminals and inland terminals in hinterland haulage for a horizontally fully integrated intermodal freight transport operator at the tactical container flow level. An intermodal freight transport network (IFTN) model is first developed to capture the key characteristics of intermodal freight transport such as the modality change phenomena at intermodal terminals, physical capacity constraints of the network, time-dependent transport times on freeways, and time schedules for trains and barges. After that, the intermodal freight transport planning problem is formulated as an optimal intermodal container flow control problem from a system and control perspective with the use of the proposed IFTN model. To deal with the dynamic transport demands and dynamic traffic conditions in the IFTN, a receding horizon intermodal container flow control (RIFC) approach is proposed to control and to reassign intermodal container flows in a receding horizon way. This container flow control approach involves solving linear programming problems and is suited for transport planning on large-sized networks. Both an all-or-nothing approach and the proposed RIFC approach are evaluated through simulation studies. Simulation results show the potential of the proposed RIFC approach.

Keywords: Intermodal freight transport planning, intermodal container flow control, receding horizon control

1. Introduction

1.1. Motivation

In global freight transport, major deep-sea ports typically act as gateways for both import and export cargoes for certain geographical areas, for instance the Port of Rotterdam for North and West Europe. These geographical areas are considered as the hinterlands of deep-sea ports. Hinterland haulage refers to freight transport between deep-sea ports and the origins or destinations of cargoes in the hinterlands, and has become an important component in modern logistic systems. An efficient and sustainable hinterland haulage will benefit freight transport operators

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and freight forwarders by reducing their operational costs, shippers by providing high quality transport services and guaranteeing low transport costs, deep-sea ports by enhancing their competitiveness, and the society by developing a sustainable freight transport system.

However, hinterland haulage has been facing challenges from increasing cargo volumes, limited capacities of transport infrastructures, traffic congestion on freeways, traffic emission issues, etc. Another major challenge for hinterland haulage is one emerging practice known as 'slow steaming' in international shipping lines. Slow steaming refers to the phenomenon that an existing deep-sea vessel goes slower than its design speed for the sake of reducing fuel consumption and consequently emissions (Psaraftis and Kontovas, 2013). The effect of this phenomenon is a longer maritime transportation time and thus a tighter schedule for hinterland haulage. These challenges necessitate an efficient and innovative way to organize hinterland haulage.

Crainic and Kim (2007) defines intermodal freight transport as "the transportation of a load from its origin to its destination by a sequence of at least two transportation modes, the transfer from one mode to the next being performed at an intermodal terminal." In hinterland haulage, intermodal freight transport strives to organize freight transport with the integrated use of different modalities (e.g., trucks, trains, barges) over an intermodal freight transport network (IFTN). An IFTN is a network consisting of different single-mode transport networks, e.g., the freeway network, the railway network, and the inland waterway network. These single-mode transport networks connect each other at intermodal terminals. An intermodal freight transport operator is a special organization or enterprise that owns or hires transport vehicles, e.g., trucks, trains, and barges, and provides shippers with intermodal container transport services over an intermodal freight transport network. The objective of intermodal freight transport planning is to select intermodal routes and determine container flow assignments over the IFTN such that a user-supplied objective function given by intermodal freight transport operators is minimized, while considering a number of transport demands, the physical capacities of transport connections, the transport network properties, and the traffic conditions. A typical example of such an operator is European Gateway Services (`http://www.europeangatewayservices.com/`), which offers frequent rail and barge connections between the Port of Rotterdam and a growing network of inland terminals in the hinterland of the port. Freight trucks are also available at terminals for transporting containers. Operators (such as European Gateway Services operator) provide an additional motivation for the work on the transport planning problem of intermodal freight transport operators as presented in this paper. The paper van Riessen et al. (2015) investigated the service network design problem for the European Gateway Services network using a path-based and minimum flow network formulation. In this paper, we will investigate container flow control problem in intermodal freight transport planning with a developed IFTN model.

1.2. The scope of the problem

This paper investigates intermodal freight transport planning problems among deep-sea terminals and inland terminals in hinterland haulage for a horizontally fully integrated intermodal freight transport operator (similar to carriers) at the tactical container flow level. The operator is assisted with an efficient ICT system. We assume that this ICT system can measure real container transport information regarding its own operations, timely exchange freight transport related information with the ICT systems of other parties involved (e.g., obtaining the measurements of traffic conditions on freeways from the traffic management system on the road network), integrate real freight transport related information from different sources, and further facilitate the freight transport planning done by the intermodal freight transport operator.

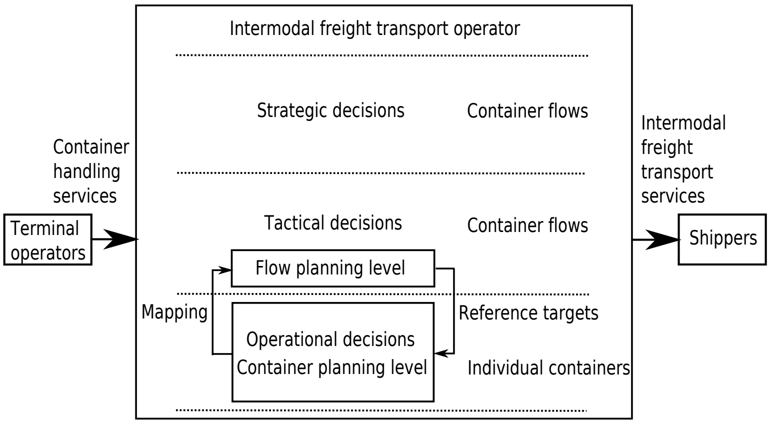

Figure 1: Overall framework of the proposed multi-level freight transport planning approach for an intermodal freight transport operator.

In maritime-based intermodal freight transport chains, hinterland haulage involves two steps: main haulage and pre-haulage or end-haulage (or collection or distribution). In this paper, we limit our scope to the main haulage, and therefore investigate intermodal freight transport planning problems among deep-sea terminals and inland terminals in hinterland haulage for intermodal freight transport operators.

Intermodal freight transport involves multiple stakeholders e.g., shippers, carriers, terminal operators, producers, consumers. There are typically two types of collaboration among these stakeholders: horizontal collaboration and vertical collaboration. This paper investigates the freight transport planning problem for a horizontally fully integrated intermodal freight transport operator, and considers other stakeholders (e.g., shippers, terminal operators) as either the customers or the service providers of this intermodal freight transport operator. This comes with the following underlying assumptions: shippers are the customers of the intermodal freight transport operator; the producers and consumers of the cargoes can be interpreted as the origins and destinations of containers, which will be specified by shippers when they make the container transport orders; terminal operators provide container handling services to the intermodal freight operator, and these container handling services are characterized by container storage capacities, container loading and unloading capacities, and times needed and cost charged for changing modalities at intermodal terminals.

Based on the decision horizon of planning problems, research efforts on intermodal freight transport are categorized into three decision-making levels: strategic level, tactical level, and operational level (see the review papers Crainic and Kim (2007); Macharis and Bontekoning (2004); Jarzemskiene (2007); Caris et al. (2008, 2013); SteadieSeifi et al. (2014)). For an intermodal freight transport operator, strategic decisions concern the infrastructure investments, e.g., whether to increase or reduce the size of intermodal transport network that this operator works on, whether to purchase more transport vehicles or rent vehicles from leasing companies; tactical decisions consider aggregated container flows and are typically about service network design and network flow planning to optimally utilize the given infrastructure, e.g., modal choice and capacity allocation on each service, service frequencies and the timetables of trains and barges, equipment planning, and container flow assignment; operational decisions consider the optimal routing of each individual container over certain service networks, e.g., intermodal routing, itinerary replanning. The operational freight transport planning problem faced by intermodal freight transport operators is typically a mixed integer optimization problem in which individual containers are directly modeled and scheduled in the planning. This problem is NP-hard and requires huge computational efforts to solve it as the number of shipments or the size of the IFTN increase.

Therefore, the current paper proposes a multi-level freight transport planning approach shown in Figure 1. Instead of directly solving the operational container transport planning problem, the multi-level planning approach addresses the planning problem within a two-level planning framework. At the flow planning level, the planning is performed at the aggregated container flow level while at the container planning level transport decisions are made for each individual container. A mapping is necessary to aggregate the transport information of individual containers to the corresponding container flow information. The advantage of the proposed multi-level planning approach is that since the planning problem at the flow planning level is formulated at the aggregated container flow level, it typically involves simple models resulting in a significant reduction of the number of integer variables so that it can be solved with a significant reduction of computational efforts compared to directly solving the operational freight transport planning problem at the individual container level. The solution to the flow planning problem can then be taken as reference for the container planning problem. This reference contains the volumes of container flows leaving each terminal through associated transport connections or switching modalities within intermodal terminals in the IFTN. The network modeling approach and the container flow control approach investigated in this paper are for the flow planning problem of the multi-level freight transport planning approach at the tactical container flow level, and will facilitate more efficient decision making for the container planning problem at the operational individual container level. The evolution of the aggregated system behavior at the tactical container flow level can be predicted with the use of the aggregated system state, the aggregated network models, and the estimated aggregated transport demands and disturbances information. The aggregated system state can be generated by exchanging and aggregating the measurements of the system state at the operational planning level within the overall multi-level freight transport planning framework shown in Figure 1. The transport demands and disturbances information could be gathered by aggregating the estimated transport information (e.g., on the second or minute scale) at the operational planning level, and or by directly making aggregated estimations (e.g., on the hour or day scale). In order to apply the network modeling approach and the container flow control approach proposed in this paper in practice, they should be integrated into an overall multi-level freight transport planning framework (see Figure 1). They need to be used together with the modeling and routing approaches at the operational individual container level, and also with the appropriate approaches to aggregate or disaggregate planning information between the tactical planning level and the operational planning level.

1.3. Receding horizon control and its applications in intermodal freight transport

In system and control theory, a system is often represented as an evolution of the system states on the basis of the system equations, the initial values of the system states, the disturbances, and the control actions. The system and control approach has been applied for resource allocation problems in container terminal operation (Alessandri et al., 2007, 2008; Nabais et al., 2013a,b). Considering intermodal freight transport as a system, the system states represent the characteristic information of the system, i.e., the number of containers at each intermodal terminal, the volumes of traffic flows on transport connections, the travel times on freeways; the disturbances are the influences placed on the system by the outside environment, i.e., the dynamic transport demands and the dynamic traffic conditions in the network; the control actions are the volumes of container flows leaving each intermodal terminal through each possible transport connection during each time interval of the whole freight transport process. These control actions should be determined by the system controller (i.e., intermodal freight transport operators) so as to achieve a certain system performance, e.g., minimizing the total delivery cost or achieving a certain model split target. For an IFTN, system equations can be derived from the internal relations among system states, disturbances, and control actions of the intermodal freight transport system. The system and control theory provides a useful way to interpret and analyze an intermodal freight transport system in terms of system states, system equations, disturbances, and control actions. Then, the online control theory can be applied to the planning problems in intermodal freight transport.

Receding horizon control (RHC) implements a sequence of optimal control problems in a receding horizon way. With the use of a system model and the current system information, RHC determines the control actions over a prediction horizon by making prediction and performing optimization, but only implements the control actions for the current time step. This prediction and optimization process proceeds in a receding horizon fashion for each time step of the whole control period by moving one time step forward. Receding horizon control is a more general variant of model predictive control (MPC), which typically focuses on on-line control. Model predictive control has been widely studied in industrial process control and more recently applied in modern traffic control (Hegyi et al., 2005; Haddad et al., 2013), power network control (Negenborn, 2007; Mc Namara et al., 2013; del Real et al., 2014), water network management (van Overloop et al., 2010; Negenborn et al., 2009), and supply chain management (Sarimveis et al., 2008; Wang and Rivera, 2008). In parallel with the various practical applications, the theoretical properties (e.g., the stability, the robustness) of MPC have also been investigated intensively (Maciejowski, 2002; Rawlings and Mayne, 2009). There are a few papers in the literature on the application of RHC and MPC in intermodal freight transport. Alessandri et al. (2007) model a deep-sea container terminal operation as a system of queues and the states and the control actions of the system are the queue lengths and container handling rates of equipment (e.g., cranes, reachstackers), respectively. The dynamic evolution of these queues is described in terms of discrete-time equations. The terminal operation is formulated as a receding horizon control problem with the aim to minimize the transfer delays of containers at the terminal. Recently, MPC has been used to control equipment (i.e., quay cranes, automated guided vehicles, and stacking cranes) for balancing throughput and energy consumption at terminals (Xin et al., 2013), to optimize the operation of terminals (Nabais et al., 2013a), and to achieve a desired modal split target at intermodal terminals (Nabais et al., 2013b).

1.4. The contributions of this paper

The above mentioned papers in Section 1.3 are focused on the applications of RHC on issues inside and related to terminals. The current paper considers both terminals and transport connections as an intermodal freight transport network. An IFTN model is developed to capture the modality change phenomena at intermodal terminals, time-dependent transport times on freeways, time schedules of trains and barges, and physical capacity limitations of the network. Meanwhile, intermodal freight transport planning problems are investigated from a system and control perspective with the use of the developed IFTN model. The container flow control actions are determined by solving both intermodal route selection and container flow assignment simultaneously as an optimization problem. Meanwhile, dynamic behavior of transport demands and traffic conditions change continuously during the entire freight delivery process. These dynamic behavior include unexpected transport order requests, transport order cancellation, the dynamic evolution of transport times on freeway links, etc. Essentially, it is hard to estimate these dynamics with a high precision for a long time period. Therefore, a receding horizon intermodal container flow control (RIFC) approach is proposed to address timely and actively the above mentioned dynamic behavior as the system disturbances in intermodal freight transport. This RIFC approach enables the possibility to consider the evolution of the IFTN while determining the control actions on container flows.

The current paper is an extended and improved version of our previous papers (Li et al., 2013, 2014). The extensions are made in the following four aspects. Firstly, the dynamic model is enhanced by taking into account the time schedules of trains and barges, and by modeling vehicle transport costs as a combination of time-dependent vehicle transport costs and distance-dependent vehicle transport costs. Secondly, we investigate intermodal freight transport from a system and control point of view using the extended IFTN model, and propose an RIFC approach to control and reassign container flows over the IFTN. This container flow control approach involves solving linear programming problems and is suited for transport planning on large-sized networks. Thirdly, the proposed dynamic IFTN model and the RIFC approach are applied to an IFTN in the Netherlands with different transport demand scenarios. The prediction errors on transport demands and traffic conditions in the IFTN are also examined in the simulation study. Moreover, as minor extensions, a multi-class version of the nonlinear and non-convex speed-density relation model and an iterative linear programming method are proposed to include the impact of freight truck flows generated by the transport operator on transport times on some special freeway cases and solve the corresponding container flow control problem, respectively.

1.5. Paper organization

The remainder of this paper is organized as follows. Section 2 reviews the existing literature on intermodal freight transport planning with emphases on its relation with unimodal freight transport, intermodal route selection, and intermodal container flow assignment. After presenting an IFTN model, Section 3 derives the optimal container flow control problem from a system and control perspective. A receding horizon intermodal container flow control approach is presented in Section 4 to address the dynamic behavior of transport demands and transport networks. In Section 5, simulation studies are conducted to illustrate the potential of the RIFC approach. Conclusions and further research directions are given in Section 6.

2. Literature review on intermodal freight transport planning

Intermodal freight transport planning involves three basic issues: its relation with unimodal freight transport, intermodal route selection, and intermodal container flow assignment. The following subsections review research work that has been done on these basic issues.

2.1. Intermodal freight transport vs unimodal freight transport

The fundamental difference between intermodal freight transport and unimodal freight transport is the possibility to use and timely switch among more than one mode of transport in the freight delivery process. A large body of literature has been devoted to develop network assignment methods in unimodal transport networks. The review papers (Peeta and Ziliaskopoulos, 2001; Assad, 1980; Crainic et al., 1984; Meng et al., 2014) and the books (Daganzo, 1997; de Dios Ortúzar and Willumsen, 2011; Pachl, 2009; Daggett, 1955; Sys and Vanelslander, 2011) present a comprehensive summary of unimodal network assignment methods. However, when directly applied to container flow assignment in intermodal freight transport networks these unimodal network assignment methods will typically lead to suboptimal assignment decisions since they do not take into account the times and costs needed to change from one modality to another. Moreover, there are also other specific issues associated with intermodal freight transport, e.g., the need to simultaneously take into account various characteristics and behavior of different modalities in transport planning, pursue modal split targets, and integrate transport and safety regulations of different modalities. Therefore, it is important to explicitly consider these intermodal aspects when planning intermodal freight transport.

2.2. Intermodal route selection approaches

Intermodal route selection involves the selection of routes for shipments through an IFTN. Intermodal route selection is typically formulated as a shortest path problem. The intermodal route selection approaches can be categorized into three main directions: the direct shortest-path-algorithm methods, the dynamic programming based methods, and the decomposition based methods.

The direct shortest-path-algorithm methods have been intensively investigated in the literature. A number of intermodal route selection methods have been developed on the basis of the shortest path algorithm and its different variants. Barnhart and Ratliff (1993) used a shortest path procedure or a matching and bi-matching algorithm (depending on the cost structure of railways) to select intermodal routes with the minimum transport cost on a rail/road combination. Boardman et al. (1997) presented a K-shortest path algorithm to determine the K least expensive modal combinations for all origin-destination pairs. For the case of time-dependent arc travel times and modality switching delays, a time-dependent intermodal optimum path algorithm has been presented by Ziliaskopoulos and Wardell (2000). The algorithm defines the label of one node as the cost or distance from a particular root node to this node in the network. The algorithm begins at the destination nodes and solves an optimality equation that is a necessary and sufficient condition for a label to be optimum in an iterative way and updates the value of labels during the iteration process of the algorithm.

The dynamic programming based methods adopt the methodology of dynamic programming to improve efficiency in solving complex intermodal route selection problems. Grasman (2006) derived dynamic programming formulations of an intermodal routing problem. The problem was solved by using Dijkstra's algorithm to find both a least cost route and a least lead time route subject to lead time and total cost, respectively. Cho et al. (2012) presented a weighted constrained shortest path problem model of the international container transport for both imports and exports. A dynamic programming algorithm that utilizes substructures of the original problem was used to find Pareto optimal transport routes with the objective of minimizing transport cost and transport time simultaneously. To implement this dynamic programming algorithm, a label setting algorithm together with pruning rules was selected to solve the constrained shortest path problem.

The decomposition based methods partition the original IFTN into small sub-networks in order to reduce the complexity of the intermodal route selection problem. Chang (2008) presented a heuristic algorithm based on relaxation and decomposition techniques to solve an international intermodal routing problem considering the time-dependency nature of the transport network. The corresponding subproblems after the decomposition were solved by existing or slightly modified shortest path algorithms. A parallel algorithm for computing a global shortest path solution in a transport network with multiple modalities and time-dependent transport times and costs was discussed in Ayed et al. (2011) based on the decomposition of the transport network according to regions and their associated transport modes. This algorithm involves multiple executions of a so-called inter modal task, which essentially computes the shortest paths from a starting point to any possible destinations in the hypergraph representation of the transport network.

However, the above intermodal route selection approaches typically do not take into account the capacity constraints of the network. Therefore, intermodal container flow assignment approaches are needed to assign container flows to the intermodal routes resulting from these intermodal route selection approaches.

2.3. *Intermodal container flow assignment approaches*

After the process of intermodal route selection, a list of candidate intermodal routes are typically selected with the aim to minimize a user-supplied objective function given by the intermodal freight transport operator, e.g., the total transport cost, the total transport time. These candidate intermodal routes are ordered according to their corresponding user-supplied objective function values. For intermodal container flow assignment, an intermodal freight transport operator determines at the origin node how much volumes of transport demands are assigned to each of the candidate routes leading to the destinations. The traditional freight assignment approaches can be categorized into four groups: all-or-nothing, equilibrium, stochastic multi-flow, and stochastic equilibrium (Jourquin, 2006). This categorization is based on two characteristic features: whether or not capacity constraints are taken into account and whether or not the variable perception of costs by users is considered. Capacity constraints refer to the limited capacity of links, which is typically captured by adding time penalties when traffic volumes on links surpass certain levels. The feature of the variable perception of costs reflects whether freight flows are assigned to the candidate intermodal routes only considering the lowest generalized cost, or whether there is also some stochasticity that influence the assignment of freight flow over several routes. These four groups of assignment approaches have been extensively used in the strategic and tactical level of freight transport planning. A recent analysis of these approaches was presented by Maia and do Couto (2013).

Typically, an all-or-nothing approach is used in practice to assign container flows in the intermodal freight transport planning. This approach assigns the entire volume of the transport demand to the route with the minimum value of the user-supplied objective function when considering unlimited capacities of transport connections. In the case of transport connections with limited capacity, transport demands will be assigned first to the route with the minimum objective value, and then to the next best candidate intermodal route, until these transport demands are completely served. This all-or-nothing approach is a greedy algorithm that can be easily implemented. However, this approach is not able to take into account the effect of container flow assignments on traffic conditions of the IFTN and will in general lead to a higher freight delivery cost. Therefore, new container flow assignment approaches are needed to efficiently conduct intermodal freight transport planning.

3. Intermodal container flow control

Intermodal freight transport has several characteristics, e.g., modality changes at intermodal terminals, physical capacity constraints of terminals and transport connections, time-dependent transport times on freeways, time schedules for trains and barges, due time requirements for freight delivery, etc. In this section, an IFTN model is developed from a container flow perspective to capture these characteristics, and the flow planning problem within an overall multi-level freight transport planning approach for intermodal freight transport planning is formulated as an intermodal container flow control problem at the tactical container flow level.

3.1. An IFTN model

An IFTN can be represented as a directed graph $\mathscr{G}(\mathscr{V},\mathscr{E},\mathscr{M})$. The node set $\mathscr{V} = \mathscr{V}_{\text{road}} \cup \mathscr{V}_{\text{rail}} \cup \mathscr{V}_{\text{water}} \cup \mathscr{V}_{\text{store}}$ is a finite nonempty set with the sets $\mathscr{V}_{\text{road}}$, $\mathscr{V}_{\text{rail}}$, $\mathscr{V}_{\text{water}}$, and $\mathscr{V}_{\text{store}}$ representing truck terminals, train terminals, barge terminals, and storage yards shared by different single-model terminals inside each intermodal terminal of the network, respectively. Single-model terminals are separately presented even when they are part of a physical intermodal terminal. The cardinalities of the node set $\mathscr{V}$, the truck-node set $\mathscr{V}_{\text{road}}$, the train-node set $\mathscr{V}_{\text{rail}}$, the barge-node set $\mathscr{V}_{\text{water}}$, and the store-node set $\mathscr{V}_{\text{store}}$ are $|\mathscr{V}| = N_{\text{node}}$, $|\mathscr{V}_{\text{road}}| = N_{\text{road}}$, $|\mathscr{V}_{\text{rail}}| = N_{\text{rail}}$, $|\mathscr{V}_{\text{water}}| = N_{\text{water}}$, and $|\mathscr{V}_{\text{store}}| = N_{\text{store}}$, respectively. The set $\mathscr{M} = \mathscr{M}_1 \cup \mathscr{M}_2$ represents transport modes and modality change types in the network with $\mathscr{M}_1 = \{\text{road}, \text{rail}, \text{water}, \text{store}\}$ and $\mathscr{M}_2 = \{m_1 \to m_2 | m_1, m_2 \in \mathscr{M}_1 \text{ and } m_1 \neq m_2\}$. The link set $\mathscr{E} \subseteq \mathscr{V} \times \mathscr{V} \times \mathscr{M}$ represents all available transport connections among nodes. A link (i, j, m) with $i, j \in \mathscr{V}$ and $m \in \mathscr{M}$ will be denoted by $l_{i,j}^{m}$ in the network. According to whether a modality change happens or not on one link, this link is categorized as transfer link or transport link. The cardinalities of the link set $\mathscr{E}$ and three link sets with different modalities are $|\mathscr{E}| = N_{\text{link}}$, $N_{\text{link}}^{\text{road}}$, $N_{\text{link}}^{\text{rail}}$, and $N_{\text{link}}^{\text{water}}$. Figure 2 presents an IFTN model to illustrate the terms mentioned above. The nodes 1^{R}, 1^{T}, 1^{W}, and 1^{S} represent the truck terminal, the train terminal, the barge terminal and the storage yard at intermodal terminal 1, respectively. The dotted blue arcs, the solid black arcs, the dashed red arcs, and the dash-dotted green arcs respectively indicate 4 transport links of the inland waterway network, 8 transport links of the road network, 2 transport links of the railway network, and 30 transfer links among four different types of transport modes (barges, trucks, trains, and store) at nodes of the IFTN. This IFTN model represents modality changes at intermodal terminals in terms of transfer links, which enables the analysis of both the transport connections and the modality changes in the same and explicit way.

Transport demand information provides the origin and destination pair of each transport demand and its volume. All origin and destination pairs belong to the set $\mathscr{O}_{\text{od}} \subseteq \mathscr{V} \times \mathscr{V}$, and the cardinality of set $\mathscr{O}_{\text{od}}$ is $|\mathscr{O}_{\text{od}}| = n$. For each transport demand with an origin and destination pair $(o,d) \in \mathscr{O}_{\text{od}}$, we denote its volume for time step k as $d_{o,d}(k)$. The IFTN model is a discrete-time model with T_{s} (h) as the time step size. Since the intermodal container flow control approach proposed in this paper works at the tactical freight transport level, the use of a common discrete time step for all modalities (i.e., trucks, trains, and barges) in the dynamic network model is reasonable. The planning horizon of the intermodal freight transport is $N \cdot T_{\text{s}}$ (h) with $N \in \mathbb{N}\backslash\{0\}$. The IFTN model consists of three parts: node behavior, link behavior, and the interconnections among nodes and links within the network. The above mentioned behavior will be modeled in more detail in the following subsections.

Before introducing the IFTN model, the main assumptions that are made throughout the modeling approach are listed:

- A common discrete time step is used for all modalities (i.e., trucks, trains, and barges) in the network model.

- Containers coming from each transport demand will immediately leave the network once they arrive at their destinations.

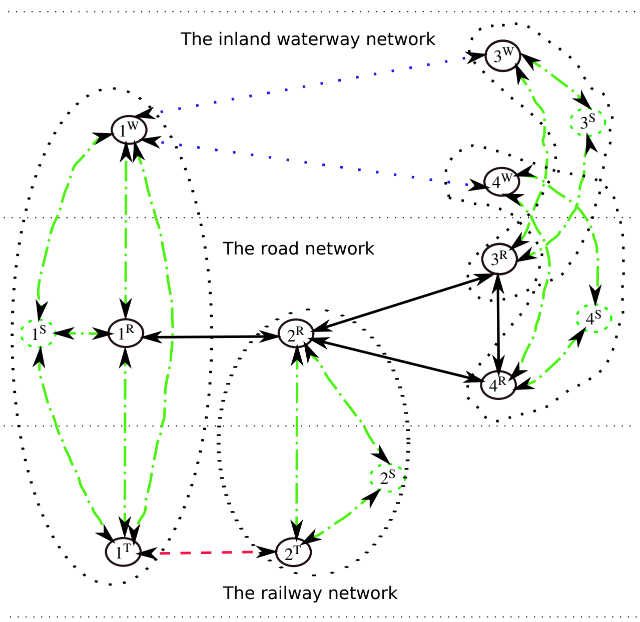

Figure 2: An IFTN model. Each doubled-headed arc in the figure represents two directed links with opposite directions.

- The link transport time is determined when container flows enter a particular link and it is assumed to be fixed for these container flows for the remaining time that will be spent to travel to the end of the link.
- Trains are operated under predetermined timetables on the railway links. Timetables for trains are predetermined in such a way that only one train can be loaded with containers at a specific time for each link of the railway network.
- Timetables for barges are modeled in the same way as that for trains.
- The distance-dependent transport cost is only incurred when a vehicle leaves the link.

Since this paper analyzes intermodal freight transport planning problems at the tactical container flow level, the above main assumptions are reasonable at the level of details that this paper interests in.

3.1.1. Node behavior

The behavior of node i is formulated as

$$x_{i,o,d}(k+1) = x_{i,o,d}(k) + \sum_{(j,m)\in\mathcal{N}_i^{\mathrm{in}}} y^m_{j,i,o,d}(k)T_{\mathrm{s}} - \sum_{(j,m)\in\mathcal{N}_i^{\mathrm{out}}} u^m_{i,j,o,d}(k)T_{\mathrm{s}} + d^{\mathrm{in}}_{i,o,d}(k)T_{\mathrm{s}} - d^{\mathrm{out}}_{i,o,d}(k)T_{\mathrm{s}}, \quad \forall(o,d)\in\mathcal{O}_{\mathrm{od}}, \forall i,j\in\mathcal{V}, \forall m\in\mathcal{M}, \forall k, \tag{1}$$

where

- $x_{i,o,d}(k)$ (TEU) is the number of containers corresponding to transport demand with origin and destination pair (o,d) and staying at node i at time $k\cdot T_{\mathrm{s}}$.

- $y^m_{j,i,o,d}(k)$ (TEU/h) is the container flow corresponding to transport demand with origin and destination pair (o,d) and entering node i through link $l^m_{j,i}, (j,m) \in \mathscr{N}_i^{\text{in}}$ for time step k where the set $\mathscr{N}_i^{\text{in}}$ is defined as

$$\mathscr{N}_i^{\text{in}} = \{(j,m) \mid l^m_{j,i} \text{ is an incoming link for node } i\}.$$

  The value of $y^m_{j,i,o,d}(k)$ equals zero when $i = o$ (which implies that node i is actually the origin node o of this transport demand).

- $u^m_{i,j,o,d}(k)$ (TEU/h) is the container flow corresponding to transport demand with origin and destination pair (o,d) and leaving node i through link $l^m_{i,j}, (j,m) \in \mathscr{N}_i^{\text{out}}$ for time step k where the set $\mathscr{N}_i^{\text{out}}$ is defined as

$$\mathscr{N}_i^{\text{out}} = \{(j,m) \mid l^m_{i,j} \text{ is an outgoing link for node } i\}.$$

  The value of $u^m_{i,j,o,d}(k)$ equals zero when $i = d$ (which implies that node i is actually the final destination node d of this transport demand).

- $d^{\text{in}}_{i,o,d}(k)$ (TEU/h) is the container flow corresponding to transport demand with origin and destination pair (o,d) and entering node i from the outside of the network for time step k. The value of $d^{\text{in}}_{i,o,d}(k)$ equals $d_{o,d}(k)$ when $i = o$, and otherwise it is zero.

- $d^{\text{out}}_{i,o,d}(k)$ (TEU/h) is the container flow corresponding to transport demand with origin and destination pair (o,d) and arriving at the final destination node i for time step k. The value of $d^{\text{out}}_{i,o,d}(k)$ equals $\sum_{(j,m)\in\mathscr{N}_i^{\text{in}}} y^m_{j,i,o,d}(k)$ when $i = d$, and otherwise it is zero.

The corresponding constraints for node i can be formulated as

$$\sum_{(o,d)\in\mathscr{O}_{\text{od}}} \sum_{(j,m)\in\mathscr{N}_i^{\text{in}}} y^m_{j,i,o,d}(k) + d^{\text{in}}_{i,o,d}(k) \leq h_i^{\text{in}}, \quad \forall i \in \mathscr{V}, \forall k, \tag{2}$$

$$\sum_{(o,d)\in\mathscr{O}_{\text{od}}} x_{i,o,d}(k) \leq S_i, \quad \forall i \in \mathscr{V}, \forall k, \tag{3}$$

$$\sum_{(o,d)\in\mathscr{O}_{\text{od}}} \sum_{(j,m)\in\mathscr{N}_i^{\text{out}}} u^m_{i,j,o,d}(k) + d^{\text{out}}_{i,o,d}(k) \leq h_i^{\text{out}}, \quad \forall i \in \mathscr{V}, \forall k, \tag{4}$$

where

- h_i^{in} (TEU/h) and h_i^{out} (TEU/h) are the maximal container unloading and loading rates of the equipment at node i, respectively.

- S_i (TEU) is the storage capacity at node i.

3.1.2. Link behavior

Transport links with different modalities in the IFTN exhibits both common behaviors and characteristic behaviors. Therefore, we first formulate the common behavior for all links in the network, and then derive individual models for links with different modalities on the basis of their particular link properties i.e., the density-speed relations on freeways, and time schedules for trains and barges.

The behavior of link $l_{i,j}^m$ is formulated as

$$q_{i,j,o,d}^{m,\text{out}}(k) = \sum_{k_e \in \mathcal{K}_e(k)} q_{i,j,o,d}^{m,\text{in}}(k_e), \quad \forall (i,j,m) \in \mathcal{E}, \forall (o,d) \in \mathcal{O}_{\text{od}}, \forall k, \tag{5}$$

$$x_{i,j,o,d}^m(k+1) = x_{i,j,o,d}^m(k) + \left(q_{i,j,o,d}^{m,\text{in}}(k) - q_{i,j,o,d}^{m,\text{out}}(k) \right) T_{\text{s}}, \quad \forall (i,j,m) \in \mathcal{E}, \forall (o,d) \in \mathcal{O}_{\text{od}}, \forall k, \tag{6}$$

where

- $q_{i,j,o,d}^{m,\text{out}}(k)$ (TEU/h) is the container flow corresponding to transport demand with origin and destination pair (o,d) and leaving link $l_{i,j}^m$ for time step k.
- $q_{i,j,o,d}^{m,\text{in}}(k)$ (TEU/h) is the container flow corresponding to transport demand with origin and destination pair (o,d) and entering link $l_{i,j}^m$ for time step k.
- $\mathcal{K}_e(k)$ is defined as the set $\{k_e \mid k - t_{i,j}^{m,\max} \leq k_e \leq k-1 \text{ and } k_e + t_{ij}^m(k_e) = k\}$.
- $x_{i,j,o,d}^m(k)$ (TEU) is the number of containers corresponding to transport demand with origin and destination pair (o,d) and traveling in link $l_{i,j}^m$ at time $k \cdot T_{\text{s}}$.
- $t_{i,j}^m(k)T_{\text{s}}$ (h) is the transport time on link $l_{i,j}^m$ at time $k \cdot T_{\text{s}}$. We assume that $T_{i,j}^m(k) = t_{i,j}^m(k)T_{\text{s}}$ for positive integer $t_{i,j}^m(k)$ where $t_{i,j}^m(k) \leq t_{i,j}^{m,\max}$ always holds. The maximum transport time on link $l_{i,j}^m$ is $t_{i,j}^{m,\max}T_{\text{s}}$ (h).

The corresponding constraints for link $l_{i,j}^m$ can be formulated as

$$\sum_{(o,d) \in \mathcal{O}_{\text{od}}} q_{i,j,o,d}^{m,\text{in}}(k) \leq C_{i,j}^{m,\text{in}}(k), \quad \forall (i,j,m) \in \mathcal{E}, \forall k, \tag{7}$$

where

- $C_{i,j}^{m,\text{in}}(k)$ (TEU/h) is the maximum entering container flow of link $l_{i,j}^m$ for time step k.

3.1.3. Freeway links behavior

In the road network, transport times on the freeway links are influenced by the traffic volumes on these links. The modeling approach for the behavior of freeway links in this section is elaborated as follows. The proposed intermodal container flow control approach takes into account the effect of traffic conditions for modeling the transport time on freeways in intermodal freight transport planning. There are a number of possible models to represent the relationship between transport time and traffic conditions on freeway links, e.g., simple structured and static models found by historical data analysis, the link transmission model (Yperman, 2007), and other complex dynamic models (Daganzo, 1997). In this paper, we propose to use a speed-density relation with a fundamental-diagram-like shape to model transport times on freeways. We motivate the use of the proposed approach considering the fact that there are already some fundamental-diagram-shape-like models (i.e., the macroscopic fundamental diagram model, or the network fundamental diagram model) available in literature to model speed-density relationships for much larger spatial and temporal urban areas (Daganzo, 2007; Geroliminis and Daganzo, 2008; Daganzo and Geroliminis, 2008; Geroliminis and Sun, 2011b) and freeway networks (Cassidy et al., 2011; Geroliminis and Sun, 2011a; Chow, 2013). The traffic flow speed on link $l_{i,j}^{\text{road}}$ for time step k, $v_{i,j}^{\text{road}}(k)$, and the corresponding transport time, $t_{i,j}^{\text{road}}(k)$, are derived as:

$$v_{i,j}^{\text{road}}(k) = \mathbf{max}\left(v_{i,j,\text{free}}^{\text{road}} \exp\left[-\frac{1}{a_{i,j}^{\text{road}}} \left(\frac{\rho_{i,j}^{\text{road}}(k)}{\rho_{i,j,\text{crit}}^{\text{road}}} \right)^{a_{i,j}^{\text{road}}} \right], v_{\min} \right), \tag{8}$$

$$t_{i,j}^{\text{road}}(k) = \mathbf{round}\left(\frac{L_{i,j}^{\text{road}}}{v_{i,j}^{\text{road}}(k)} \frac{1}{T_{\text{s}}} \right), \tag{9}$$

where

- $L_{i,j}^{\text{road}}$ (km), $\rho_{i,j}^{\text{road}}(k)$ (veh/km/lane), $v_{i,j}^{\text{road}}(k)$ (km/h), and $t_{i,j}^{\text{road}}(k)$ (h) are the length of, the traffic density on, the average speed on, and the average transport time on link $l_{i,j}^{\text{road}}$ for time step k, respectively.

- $v_{i,j,\text{free}}^{\text{road}}$, $a_{i,j}^{\text{road}}$, and $\rho_{i,j,\text{crit}}^{\text{road}}$ are the model parameters of the speed-density relation model. The minimum speed on freeways links is $v_{\min}$ (km/h).

- $\rho_{i,j}^{\text{road,max}}$ (veh/km/lane) is the maximum allowed traffic density on link $l_{i,j}^{\text{road}}$. The maximum number of transport time step $t_{i,j}^{\text{road,max}}$ (which is used in the lower boundary of the link behavior equation) is determined by $\rho_{i,j}^{\text{road,max}}$ through equations (8) and (9).

It is noteworthy that the nonlinear density-speed relation model (8)–(9) for freeways can in general be used in an off-line fashion.

Remark 1. *A large-size transport operator might be able to influence the traffic conditions on freeways with its own freight truck flows under certain circumstances. These circumstances could occur on the freeways that connect a deep-sea port with nearby inland terminals around the port areas when the traffic densities on these freeways are quite high during rush hours. To capture the impact of freight truck flows induced by the transport operator, a multi-class version of the speed-density relation can be used Li et al. (2013). The freight truck flow speed on link $l_{i,j}^{\text{road}}$ for time step k, $v_{i,j}^{\text{road,truck}}(k)$, and the corresponding transport time, $t_{i,j}^{\text{road,truck}}(k)$, are then given by*

$$\rho_{i,j}^{\text{road,total}}(k) = \frac{L_{\text{truck}}}{L_{\text{other}}} \left(\sum_{(o,d)\in\mathscr{O}_{\text{od}}} \frac{1}{L_{i,j}^{\text{road}} \lambda_{i,j}^{\text{road}}} x_{i,j,o,d}^{\text{road}}(k) \right) + \rho_{i,j}^{\text{road,other}}(k), \tag{10}$$

$$v_{i,j}^{\text{road,truck}}(k) = \mathbf{max}\left(v_{i,j,\text{free}}^{\text{road,truck}} \exp\left[-\frac{1}{a_{i,j}^{\text{road,truck}}} \left(\frac{\rho_{i,j}^{\text{road,total}}(k)}{\rho_{i,j,\text{crit}}^{\text{road}}} \right)^{a_{i,j}^{\text{road,truck}}} \right], v_{\min} \right), \tag{11}$$

$$t_{i,j}^{\text{road,truck}}(k) = \mathbf{round}\left(\frac{L_{i,j}^{\text{road}}}{v_{i,j}^{\text{road,truck}}(k)} \frac{1}{T_{\text{s}}} \right), \tag{12}$$

where $\rho_{i,j}^{\text{road,total}}(k)$ (veh/km/lane) and $\rho_{i,j}^{\text{road,other}}(k)$ (veh/km/lane) are the total traffic density and the traffic density induced by the other traffic on link $l_{i,j}^{\text{road}}$ for time step k respectively, L_{truck} (m) and L_{other} (m) are the typical lengths of freight trucks and other vehicles, $\lambda_{i,j}^{\text{road}}$ is the number of lanes of link $l_{i,j}^{\text{road}}$, $v_{i,j}^{\text{road,truck}}(k)$ (km/h) and $t_{i,j}^{\text{road,truck}}(k)$ (km/h) are the average speed and the *average transport time of container flow on link $l_{i,j}^{\text{road}}$ for time step k respectively, $v_{i,j,\text{free}}^{\text{road,truck}}$, $a_{i,j}^{\text{road,truck}}$, $\rho_{i,j,\text{crit}}^{\text{road,truck}}$, $\rho_{i,j,\text{crit}}^{\text{road}}$ are the model parameters of the multi-class version of the speed-density relation model. The corresponding capacity constraints for link $l_{i,j}^{\text{road}}$ can be formulated as*

$$\sum_{(o,d)\in\mathscr{O}_{\text{od}}} x_{i,j,o,d}^{\text{road}}(k) \leq \left(\rho_{i,j}^{\text{road,max}} - \rho_{i,j}^{\text{road,other}}(k)\right) \frac{L_{\text{other}}}{L_{\text{truck}}} L_{i,j}^{\text{road}} \lambda_{i,j}^{\text{road}}, \quad \forall(i,j,m)\in\mathscr{E}, \forall k. \tag{13}$$

3.1.4. Railway and inland waterway links behavior

One basic feature distinguishing railway and inland waterway transport from road transport is the existence of time schedules for trains and barges. In this paper, we model time schedules for barges in the same way as for trains. For the sake of simplicity, we will only refer to trains and the railway network in the remaining part of this section.

This paper considers scheduled trains that are operated under predetermined time schedules on the railway links. Time schedules provide the detailed information of each transport service on each transport connection of the railway network during the whole freight transport planning period, i.e., the time point at which the trains become available at the departure terminal, the capacity of trains, the handling capacity of equipment for serving trains at the departure terminal, the departure time of trains at the departure terminal, and the arrival time of trains at the destination terminal. To capture the discontinuity of transport services caused by these time schedules, time-dependent maximum entering container flows and time-dependent transport times on links of the railway network are introduced.

The basic idea is to take into account both trains waiting at the departure terminal (node) for loading containers and trains running on the railway link in the analysis and modeling of the evolution of container flows on the link. For link $l_{i,j}^{\text{rail}}$ in the railway network, we define the set of trains, $\mathscr{S}_{i,j}^{\text{rail}}$, that are scheduled to travel from terminal i to terminal j according to a pre-scheduled timetable. The cardinality of the set $\mathscr{S}_{i,j}^{\text{rail}}$ is $|\mathscr{S}_{i,j}^{\text{rail}}|$. For a scheduled train $s\in\mathscr{S}_{i,j}^{\text{rail}}$, this timetable determines the train capacity $S_{i,j,s}^{\text{rail}}$ (TEU), the time point $t_{i,j,s}^{\text{rail,available}}T_{\text{s}}$ (h) at which the scheduled train s becomes available at terminal i, the container loading capacity of equipment for serving this train $h_{i,j,s}^{\text{rail}}$ (TEU/h) at terminal i, the train departure time $t_{i,j,s}^{\text{rail,departure}}T_{\text{s}}$ (h) from terminal i, and the train arrival time $t_{i,j,s}^{\text{rail,arrival}}T_{\text{s}}$ (h) at terminal j.

Because trains are operated under predetermined time schedules, the time-dependent transport time $t_{i,j}^{\text{rail}}(k)T_{\text{s}}$ that container flows will take to arrival terminal j includes $t_{i,j,\text{waiting}}^{\text{rail}}(k)T_{\text{s}}$, the time that container flows spend waiting for the trains to depart from terminal i, and $t_{i,j,\text{traveling}}^{\text{rail}}(k)T_{\text{s}}$, the actual train traveling time on link $l_{i,j}^{\text{rail}}$. It can be calculated by

$$\begin{aligned} t_{i,j}^{\text{rail}}(k) &= t_{i,j,\text{waiting}}^{\text{rail}}(k) + t_{i,j,\text{traveling}}^{\text{rail}}(k) \\ &= \begin{cases} t_{i,j,s}^{\text{rail,arrival}} - t_{i,j,s}^{\text{rail,available}}, & \text{if } t_{i,j,s-1}^{\text{rail,departure}} < k \leq t_{i,j,s}^{\text{rail,available}}, \\ & \text{for some } s\in\mathscr{S}_{i,j}^{\text{rail}}, \\ t_{i,j,s'}^{\text{rail,arrival}} - k, & \text{if } t_{i,j,s'}^{\text{rail,available}} < k \leq t_{i,j,s'}^{\text{rail,departure}}, \\ & \text{for some } s'\in\mathscr{S}_{i,j}^{\text{rail}}. \end{cases} \end{aligned} \tag{14}$$

As been listed in Section 3.1, it is assumed that timetables for trains are predetermined in such a way that only one train can be loaded with containers at a specific time for each link of the railway network. This assumption implies that $t^{\text{rail,available}}_{i,j,s} < t^{\text{rail,departure}}_{i,j,s}$ and $t^{\text{rail,available}}_{i,j,s} > t^{\text{rail,departure}}_{i,j,s-1}$, $\forall s \in \mathscr{S}^{\text{rail}}_{i,j}$ hold on each railway link $(i, j, \text{rail}) \in \mathscr{E}$, which guarantees that the two options in equation (12) are mutually exclusive.

The maximum transport time $t^{\text{rail,max}}_{i,j} T_{\text{s}}$ (h) of link $l^{\text{rail}}_{i,j}$ is determined by

$$t^{\text{rail,max}}_{i,j} = \max_{s \in \mathscr{S}^{\text{rail}}_{i,j}} \left(t^{\text{rail,arrival}}_{i,j,s} - t^{\text{rail,available}}_{i,j,s}\right).$$

The container loading process can only start after a train becomes available at the terminal and should stop when this train departs. This implies that containers can only be loaded on train $s \in \mathscr{S}^{\text{rail}}_{i,j}$ and simultaneously enter link $l^{\text{rail}}_{i,j}$ during a time period of $\left[t^{\text{rail,available}}_{i,j,s} T_{\text{s}},\ t^{\text{rail,departure}}_{i,j,s} T_{\text{s}}\right)$. Therefore, the time-dependent maximum entering container flow $C^{\text{rail,in}}_{i,j}(k)$ for link $l^{\text{rail}}_{i,j}$ is formulated as follows

$$C^{\text{rail,in}}_{i,j}(k) = \begin{cases} h^{\text{rail}}_{i,j,s}, & \text{if } t^{\text{rail,available}}_{i,j,s} < k \le t^{\text{rail,departure}}_{i,j,s}, \text{ for some } s \in \mathscr{S}^{\text{rail}}_{i,j} \\ 0, & \text{otherwise.} \end{cases} \tag{15}$$

Each scheduled train $s \in \mathscr{S}^{\text{rail}}_{i,j}$ on link $l^{\text{rail}}_{i,j}$ is associated with a train capacity $S^{\text{rail}}_{i,j,s}$ (TEU), which imposes constraints on the total number of containers being loaded on this train during the container loading process. These constraints are formulated as follows

$$\sum_{(o,d) \in \mathscr{O}_{\text{od}}} \sum_{k_e = t^{\text{rail,available}}_{i,j,s}}^{\min\left(t^{\text{rail,departure}}_{i,j,s}, N\right)} q^{\text{rail,in}}_{i,j,o,d}(k_e) T_{\text{s}} \ \le\ S^{\text{rail}}_{i,j,s}, \quad s \in \mathscr{S}^{\text{rail}}_{i,j}, \forall (i, j, \text{rail}) \in \mathscr{E}. \tag{16}$$

3.1.5. Interactions between nodes and links

Container flows travel over an IFTN and create interactions between nodes and links. These interactions are formulated as follows

$$q^{m,\text{in}}_{i,j,o,d}(k) = u^{m}_{i,j,o,d}(k), \quad \forall\, i \in \mathscr{V}, \forall (j,m) \in \mathscr{N}^{\text{out}}_{i}, \forall (o,d) \in \mathscr{O}_{\text{od}}, \forall k, \tag{17}$$

$$y^{m}_{i,j,o,d}(k) = q^{m,\text{out}}_{i,j,o,d}(k), \quad \forall\, j \in \mathscr{V}, \forall (i,m) \in \mathscr{N}^{\text{in}}_{j}, \forall (o,d) \in \mathscr{O}_{\text{od}}, \forall k, \tag{18}$$

where

- (17) captures the interactions between node i and each of its outgoing link $l^{m}_{i,j}$. It means that the volumes of the container flows leaving node i through link $l^{m}_{i,j}$ are equal to the volumes of the container flows entering link $l^{m}_{i,j}$ for time step k.
- (18) captures the interactions between each incoming link $l^{m}_{i,j}$ and node j. It means that the volumes of the container flows leaving link $l^{m}_{i,j}$ and entering into node j are equal to the volumes of the container flows entering node j through link $l^{m}_{i,j}$ for time step k.

3.1.6. Quantities in the IFTN model

Four types of quantities exist in the IFTN model presented in Section 3.1. To make a distinction, they are listed as follows:

- Problem data (known):
$h_i^{\text{in}}, S_i, h_i^{\text{out}}, C_{i,j}^{m,\text{in}}(k), L_{i,j}^{\text{road}}, \lambda_{i,j}^{\text{road}}, L_{\text{truck}}, L_{\text{other}}, v_{i,j,\text{free}}^{\text{road,truck}}(k), a_{i,j}^{\text{road,truck}}, \rho_{i,j,\text{crit}}^{\text{road,truck}}, v_{\min},$
$t_{i,j,s}^{\text{rail,available}}(k), t_{i,j,s}^{\text{rail,departure}}(k), t_{i,j,s}^{\text{rail,arrival}}(k), h_{i,j,s}^{\text{rail}}, S_{i,j,s}^{\text{rail}}, T_s, N$
- Problem data (estimated):
$d_{i,o,d}^{\text{in}}(k), \rho_{i,j}^{\text{road,other}}(k)$
- State variables:
$x_{i,o,d}(k), x_{i,j,o,d}^{m}(k), y_{j,i,o,d}^{m}(k), q_{i,j,o,d}^{m,\text{out}}(k), d_{i,o,d}^{\text{out}}(k), x_{i,j,o,d}^{\text{road}}(k), \rho_{i,j}^{\text{road,total}}(k), v_{i,j}^{\text{road,truck}}(k),$
$t_{i,j}^{\text{road,truck}}(k), t_{i,j}^{\text{rail}}(k), t_{i,j,\text{waiting}}^{\text{rail}}(k), t_{i,j,\text{traveling}}^{\text{rail}}(k), C_{i,j}^{rail,\text{in}}(k)$
- Decision variables:
$u_{i,j,o,d}^{m}(k), q_{i,j,o,d}^{m,\text{in}}(k)$

Moreover, the last three types of quantities will be called as disturbances, system states, and control actions in the RHC formulation of the planning problem in Section 4.

3.2. Optimal intermodal container flow control

The behavior of the IFTN presented in Section 3.1 essentially capture all possible intermodal freight transport plans in the network. The intermodal container transport planning problem actually determines only one intermodal container flow transport plan that meets certain criteria. To be more specific, the aim is to determine the volumes of container flows leaving each node of the IFTN through each of its outgoing links for each time step such that the total delivery cost for serving the given transport demands is minimized.

The delivery cost structure of intermodal freight transport operators consists of vehicle transport costs, modality change costs, storage costs, the value of container transshipment time. Vehicle transport costs have two parts: time-dependent vehicle transport costs and distance-dependent vehicle transport costs. Based on this delivery cost structure, the objective function of the intermodal container transport planning is defined as

$$J = \alpha(J_1 + J_2) + J_3 + J_4 \tag{19}$$

with

$$J_1 = \sum_{(o,d)\in\mathscr{O}_{\text{od}}} w_{o,d} \left[\sum_{k=1}^{N-1} \left[\sum_{i\in\mathscr{V}} x_{i,o,d}(k)T_{\text{s}} + \sum_{(i,j,m)\in\mathscr{E}} x_{i,j,o,d}^{m}(k)T_{\text{s}}\right]\right] \tag{20}$$

$$J_2 = \sum_{(o,d)\in\mathscr{O}_{\text{od}}} w_{o,d} \left[\sum_{i\in\mathscr{V}} x_{i,o,d}(N)r_{i,d} + \sum_{(i,j,m)\in\mathscr{E}} x_{i,j,o,d}^{m}(N)r_{i,j}^{m,d}\right] \tag{21}$$

$$\begin{aligned} J_3 = \sum_{(o,d)\in\mathscr{O}_{\text{od}}} w_{o,d} \Bigg[\sum_{k=1}^{N-1} \Bigg[&\sum_{i\in\mathscr{V}} x_{i,o,d}(k)T_{\text{s}}c_{i,\text{store}}(k) + \\ &\sum_{(i,j,m)\in\mathscr{E}} x_{i,j,o,d}^{m}(k)T_{\text{s}}c_{i,j,\text{time}}^{m}(k) + y_{i,j,o,d}^{m}(k)T_{\text{s}}L_{i,j}^{m}c_{i,j,\text{distance}}^{m}(k)\Bigg]\Bigg] \end{aligned} \tag{22}$$

$$J_4 = \sum_{(o,d)\in\mathscr{O}_{\text{od}}} w_{o,d} \left[\sum_{i\in\mathscr{V}} x_{i,o,d}(N)c_{i,d} + \sum_{(i,j,m)\in\mathscr{E}} x_{i,j,o,d}^{m}(N)c_{i,j}^{m,d}\right], \tag{23}$$

where

- J_1, J_3 are the total transport time and the total transport cost of transport demands and J_2, J_4 are penalties on the unfinished transport demands at the end of the planning horizon.

- $w_{o,d} \in (0,1]$ indicates the relative priority of the transport demand (o,d); the relation $\sum_{(o,d)\in\mathscr{O}_{\text{od}}} w_{o,d} = 1$ always holds.

- $c_{i,\text{store}}(k)$ (€/TEU/h) is the container storage cost at node i for time step k.

- $c^{m}_{i,j,\text{time}}(k)$ (€/TEU/h) and $c^{m}_{i,j,\text{distance}}(k)$ (€/TEU/km) are the time-dependent and distance-dependent vehicle transport or modality change costs for time step k. For the modality change links, only the time-dependent cost is used to model the modality change cost at intermodal terminals. This implies that the distance-dependent cost of modality change links is considered to be zero.

- $r_{i,d}$ (h/TEU), $c_{i,d}$ (€/TEU), $r^{m,d}_{i,j}$ (h/TEU) and $c^{m,d}_{i,j}$ (€/TEU) are the typical transport time and the typical delivery cost for containers being transported from node i or link $l^{m}_{i,j}$ to destination node d, respectively. They can be obtained from historical data.

- α (€/h) is the value of time for intermodal freight transport operators to convert container transshipment times to their equivalent monetary costs. Since this paper considers the aggregated container flow, it is essentially not possible to directly capture the due time requirement of containers in the system model. Therefore, the value of time helps to address the due time requirement in an indirect way by adding the time cost in the objective function to push container flows to move to their destinations.

The intermodal container transport planning can be interpreted as making decisions on taking appropriate container flow control action $u^{m}_{i,j}(k)$ for each time step k on each outgoing link $l^{m}_{i,j}$ of each node i in the intermodal freight transport system such that container flows move from their origins to the destinations over the IFTN while the objective function (19) is minimized. In this system, the movement of container flows is generated by transport demands with origin and destination pairs $\mathscr{O}_{\text{od}}$ and certain volumes, and is regulated by system equations and constraints defined by the IFTN model presented in Section 3.1. At time $k \cdot T_{\text{s}}$ (h), the control actions in intermodal freight transport system, $\mathbf{u}(k) \in \mathbb{R}^{n \cdot N_{\text{link}}}$, are the container flow control actions, or specifically the volumes of container flows entering each link $l^{m}_{i,j}$ at node i; the system states, $\mathbf{x}(k) \in \mathbb{R}^{n\cdot\left(N_{\text{node}}+N_{\text{link}}+\sum_{(i,j,m)\in\mathscr{E}} t^{m,\max}_{i,j}\right)}$, contain the number of containers at each node and on each link of the IFTN and the container flow control actions for each link $l^{m}_{i,j}(k)$ in the previous $t^{m,\max}_{i,j}$ time steps; the disturbances, $\mathbf{d}(k) \in \mathbb{R}^{n\cdot\left(N_{\text{node}}+N^{\text{road}}_{\text{link}}\right)}$, comprise the volumes of container flows entering each node from the outside of the IFTN and the other traffic density on road links, i.e., $d^{\text{in}}_{i}(k)$, and $\rho^{\text{road,other}}_{i,j}(k)$; the system outputs, $\mathbf{y}(k) \in \mathbb{R}^{n\cdot N_{\text{node}}}$, are the volumes of container flows leaving each link of the IFTN, i.e., $d^{\text{out}}_{i}(k)$. The intermodal container transport planning problem is thus formulated as the following optimal intermodal container flow control problem:

$$\min_{\mathbf{x},\mathbf{u},\mathbf{y}} J(\mathbf{x},\mathbf{u},\mathbf{y}) \tag{24}$$

subject to

$$\mathbf{x}(k+1) = \mathbf{f_1}\left(\mathbf{x}(k),\mathbf{u}(k),\mathbf{d}(k),\mathbf{y}(k)\right), \tag{25}$$

$$\mathbf{y}(k+1) = \mathbf{f_2}\left(\mathbf{x}(k+1),\mathbf{u}(k),\mathbf{d}(k)\right), \tag{26}$$

$$\mathbf{g}\left(\mathbf{x}(k+1),\mathbf{u}(k),\mathbf{d}(k),\mathbf{y}(k+1)\right) \leq 0, \quad k = 0,\ldots,N-1, \tag{27}$$

$$\mathbf{x}(0) = \mathbf{x}_0, \quad \mathbf{d}(k) = \mathbf{d}_k \tag{28}$$

where $\mathbf{u}(k)$ and $\mathbf{u}$ are two vectors that contain the container flow control actions at nodes of the IFTN for time step k or over the whole planning period $[0, N \cdot T_\mathrm{s})$ (h) respectively, and the vectors $\mathbf{x}(k)$, $\mathbf{x}$, $\mathbf{y}(k)$, $\mathbf{y}$, $\mathbf{d}(k)$, and $\mathbf{d}$ are defined in the same way; $\mathbf{x}_0$ are the initial states of the system; and $\mathbf{d}_k$ are the disturbances for time step k and given by transport demand and traffic condition information in the system.

4. Receding horizon intermodal container flow control

The intermodal freight transport planning problem considered in this paper has two major characteristics: 1) to address dynamic behaviors of transport demands and traffic conditions in the IFTN by applying replanning strategies; 2) to determine both intermodal route and container flow assignment simultaneously by solving an optimization problem. Receding horizon control approaches can cope with these two characteristics in a proper manner. First, RHC solves a sequence of optimal container flow control problems in a receding horizon fashion. For each time step k of the whole simulation period $N_\mathrm{sim} T_\mathrm{s}$ (h), an optimal intermodal container flow control problem (24) for a finite prediction horizon $\left[k \cdot T_\mathrm{s}, \left(k + N_\mathrm{p}\right) \cdot T_\mathrm{s}\right)$ (h) is solved to find the optimal container flow control actions $\tilde{\mathbf{u}}(k)$ on the basis of the IFTN model, the current system states $\mathbf{x}(k)$, the (probably estimated) information of system disturbances $\tilde{\mathbf{d}}(k)$ over the prediction horizon, and only the optimal intermodal container flow control actions for time step k are actually applied. For the next time step $k+1$, the same control and optimization procedure is implemented with the updated system states $\mathbf{x}(k+1)$ and system disturbances $\tilde{\mathbf{d}}(k+1)$. Secondly, the optimal intermodal container flow control problem (24) solved for each time step evaluates the possible intermodal routing and container flow assignment options in terms of control actions for the finite prediction horizon $\left[k \cdot T_\mathrm{s}, \left(k + N_\mathrm{p}\right) \cdot T_\mathrm{s}\right)$ (h). The receding horizon intermodal container flow control (RIFC) problem for time step k can be stated as:

$$\min_{\tilde{\mathbf{x}}(k), \tilde{\mathbf{u}}(k), \tilde{\mathbf{y}}(k), \tilde{\mathbf{d}}(k)} J(\tilde{\mathbf{x}}(k), \tilde{\mathbf{u}}(k), \tilde{\mathbf{d}}(k), \tilde{\mathbf{y}}(k)) \tag{29}$$

subject to

$$\mathbf{x}(k+1+l) = \mathbf{f_1}(\mathbf{x}(k+l), \mathbf{u}(k+l), \mathbf{d}(k+l), \mathbf{y}(k+l)), \tag{30}$$

$$\mathbf{y}(k+1+l) = \mathbf{f_2}(\mathbf{x}(k+1+l), \mathbf{u}(k+l), \mathbf{d}(k+l)), \tag{31}$$

$$\mathbf{g}(\mathbf{x}(k+1+l), \mathbf{u}(k+l), \mathbf{d}(k+l), \mathbf{y}(k+1+l)) \leq 0, \quad l = 0, \ldots, N_\mathrm{p} - 1, \tag{32}$$

$$\mathbf{x}(k) = \mathbf{x}_k, \quad \mathbf{d}(k) = \mathbf{d}_k \tag{33}$$

where $\tilde{\mathbf{x}}(k)$, $\tilde{\mathbf{u}}(k)$, $\tilde{\mathbf{d}}(k)$, and $\tilde{\mathbf{y}}(k)$ are defined in the same way as $\mathbf{x}(k)$, $\mathbf{u}(k)$, $\mathbf{d}(k)$, and $\mathbf{y}(k)$ in the optimal container flow control problem (24), but for a prediction horizon $\left[k \cdot T_\mathrm{s}, \left(k + N_\mathrm{p}\right) \cdot T_\mathrm{s}\right)$ (h) instead of only for time step k. Because the nonlinear speed-density relations (8)–(9) can be evaluated in an off-line fashion, this receding horizon intermodal container flow control problem is essentially a linear programming (LP) problem. For time step k, the receding horizon intermodal container flow control approach involves an LP problem with $n \cdot N_\mathrm{p} \cdot N_\mathrm{link}$ variables, and $N_\mathrm{p} \cdot \left(4N_\mathrm{node} + 3N_\mathrm{link} + N^\mathrm{train}_\mathrm{scheduled}(k) + N^\mathrm{barge}_\mathrm{scheduled}(k)\right)$ inequality constraints. The scheduled trains and barges in the network during the prediction horizon $\left[k \cdot T_\mathrm{s}, \left(k + N_\mathrm{p}\right) \cdot T_\mathrm{s}\right)$ (h) are $N^\mathrm{train}_\mathrm{scheduled}(k)$ and $N^\mathrm{barge}_\mathrm{scheduled}(k)$, respectively. This LP problem has a polynomial time complexity and can be solved efficiently with state-of-the-art algorithms e.g. the simplex algorithm, the interior-point algorithm (Pardalos and Resende, 2002).

Remark 2. *When the speed-density relations presented in **Remark 1** are used to model traffic behavior on freeways, the corresponding receding horizon intermodal container flow control problem becomes a nonlinear and non-convex optimization problem. A multi-start iterative linear programming (ILP) method can be adopted to solve this receding horizon intermodal container flow control problem. The ILP method involves an iterative implementation of an LP step and an update step until certain iteration stopping criteria are met. In the first step, the problem (27)–(31) is solved as an LP problem by considering fixed freeway transport times. After that, the second step updates freeway transport times using the flow control actions and the predicted system states obtained in the previous LP step and the multi-class version of the speed-density relation model (10)–(12). For the particular nonlinearity of this freeway model, the evolution of the objective function during the iteration process for each time step does not always converge, but it may result in oscillations. Therefore, a so-called stopping window method is proposed to identify the oscillations during iterations. This method defines a stopping window with a length of N_{window} iterations and works as follows: at each iteration $s \geq 2 \cdot N_{\text{window}}$, check whether one of the earlier N_{window} stopping windows has the same characteristic parameters (i.e., the minimum, mean, and maximum values of the objective functions within the stopping window.) as that of the current stopping window; if yes, take the solution corresponding to the minimum value of the objective function in the current stopping window as the optimal solution and terminate the iteration procedure; if not, move to the next iteration. This iteration procedure will be terminated at a pre-defined maximum number of iterations.*

5. Simulation study

The RIFC approach is investigated for intermodal freight transport planning from Rotterdam to Venlo over an IFTN in The Netherlands. Section 5.1 introduces the basic setting of the intermodal freight transport planning problem. The RIFC approach and the all-or-nothing approach (as introduced in Section 2.3) are applied and compared in Section 5.2. Section 5.3 and Section 5.4 further examine the performance of the RIFC approach under five different demand scenarios and for four prediction error levels on future transport demands and traffic conditions in the IFTN.

5.1. The intermodal freight transport planning problem

Figure 3 illustrates the topology of an IFTN connecting Rotterdam to Venlo. The corresponding IFTN model with distances and transport times on links is shown in Figure 4. The number 1, 2, 3, 4, 5, and 6 in the labels of the nodes in the network model refer to Rotterdam, Dordrecht, Utrecht, Tilburg, Nijmegen and Venlo, respectively. The dotted blue arcs, the solid black arcs, the dashed red arcs, and the dash-dotted green arcs respectively indicate 3 transport links of the inland waterway network, 6 transport links of the road network, 3 transport link of the railway network, and 27 transfer links among four different types of transport modes (barges, trucks, trains, and store) at nodes of the network. Travel times on transport links, i.e., $t^{\text{road}}_{1^{\text{R}},2^{\text{R}}}$, $t^{\text{road}}_{1^{\text{R}},3^{\text{R}}}$, $t^{\text{road}}_{2^{\text{R}},4^{\text{R}}}$, $t^{\text{road}}_{4^{\text{R}},6^{\text{R}}}$, $t^{\text{road}}_{3^{\text{R}},5^{\text{R}}}$, $t^{\text{road}}_{5^{\text{R}},6^{\text{R}}}$, $t^{\text{water}}_{1^{\text{W}},2^{\text{W}}}$, $t^{\text{water}}_{2^{\text{W}},5^{\text{W}}}$, $t^{\text{water}}_{2^{\text{W}},6^{\text{W}}}$, $t^{\text{rail}}_{1^{\text{T}},4^{\text{T}}}$, $t^{\text{rail}}_{1^{\text{T}},5^{\text{T}}}$ and $t^{\text{rail}}_{4^{\text{T}},6^{\text{T}}}$ are calculated with (9) and (14), respectively. For freeway links, railway links, and inland waterway links, the distance-dependent transport costs are 0.2758, 0.0635, and 0.0213 (€/TEU/km), respectively; and the time-dependent costs are 30.98, 7.54, and 0.6122 (€/TEU/h), respectively (van den Driest, 2010). Modality change costs and modality change times are 23.89 (€/TEU) and 2 (h) among any two modes of transport, i.e., trucks, trains, and barges; and are 11.945 (€/TEU) and 1 (h)

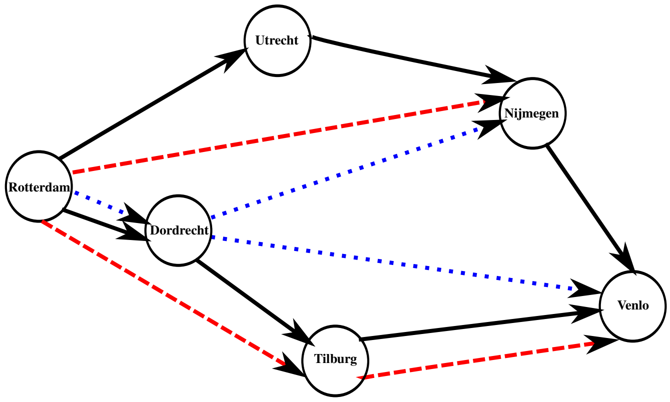

Figure 3: The topology of an IFTN from Rotterdam to Venlo. The solid black arcs, the dashed red arcs, and the dotted blue arcs indicate freeway links, railway links, and inland waterway links in the network, respectively.

between the storage and any one of the above three modalities. The storage cost at terminals for a relatively short period (i.e., 1 or 2 days) is very small or even free, therefore it is taken as 0.0001 (€/TEU/h). The typical transport time between any two nodes in the IFTN is given in Table 1. The typical delivery cost between any possible pair of nodes is approximated as the monetary cost of the corresponding typical transport time with a conversion factor of 25 (€/h). The handling capacities of loading and unloading containers at nodes of the network are taken to be unlimited. The storage capacities at five storage nodes are considered to be unlimited, while at other nodes they are 1000 (TEU). The maximum entering container flows of links with different modalities are 400 (TEU/h) for freeway links, determined by train and barge time schedules for railway and inland waterway links, and 10000 (TEU/h) for modality change links.

We consider intermodal freight transport planning for a period of 24 (h) with a time step $T_\mathrm{s} = 1$ (h). A piecewise constant container transport demand from node 1^W to node 6^R is given in Table 2. The value of time in (19) is taken as 25 (€/h). Trucks are assumed to be always available on the freeway links for delivering containers, and the parameters in (8) for freeway links are respectively $v^{\mathrm{road}}_{i,j,\mathrm{free}} = 110$ (km/h), $a^{\mathrm{road}}_{i,j} = 1.636$, and $\rho^{\mathrm{road}}_{i,j,\mathrm{crit}} = 33.5$ (veh/km/lane) (Kotsialos et al., 2002). There are two lanes on each freeway link and the minimum speed and the maximum density are 10 (km/h) and $\rho^{\mathrm{road}}_{i,j,\max} = 180$ (veh/km/lane), respectively. Freight trucks are assumed to have three times the length of other vehicles on freeways. The other traffic flows on six freeway links are given in Table 2. There are regular freight train and barge services on railway links and inland waterway links: on link $l^{\mathrm{rail}}_{1^\mathrm{T},4^\mathrm{T}}$, a train is scheduled to be available at node 1^T every 3 hours, spend 2 hours for loading containers, and then departure form node 1^T and travel $t^{\mathrm{rail}}_{1^\mathrm{T},4^\mathrm{T},\mathrm{traveling}} = 6$ hours to node 3^T; regular services on other railway links and inland waterway links are scheduled in the same way only with different actual traveling times, 3 hours, 4 hours, 4 hours, 7 hours, and 11 hours for link $l^{\mathrm{rail}}_{4^\mathrm{T},6^\mathrm{T}}$, link $l^{\mathrm{rail}}_{1^\mathrm{T},5^\mathrm{T}}$, $l^{\mathrm{water}}_{1^\mathrm{W},2^\mathrm{W}}$, $l^{\mathrm{water}}_{2^\mathrm{W},5^\mathrm{W}}$, and $l^{\mathrm{water}}_{2^\mathrm{W},6^\mathrm{W}}$, respectively. The capacities of trains and barges are 100 (TEU) and 200 (TEU), and the handling capacities of equipment for serving them are 100 (TEU/h) and 200 (TEU/h), respectively. For the above intermodal freight transport setup, the initial state of the network is taken to be empty (i.e., $x_{i,o,d}(k) = 0$ and $x^m_{i,j,o,d}(k) = 0$, $\forall (o,d) \in \mathscr{O}_{\mathrm{od}}, \forall\ (i,j,m) \in \mathscr{E}, \forall\ k \leq 0$). The simulation experiments are done with the use of a desktop computer with an Intel® Core™ i5-2400 CPU with 3.10 GHz and 4 GB RAM.

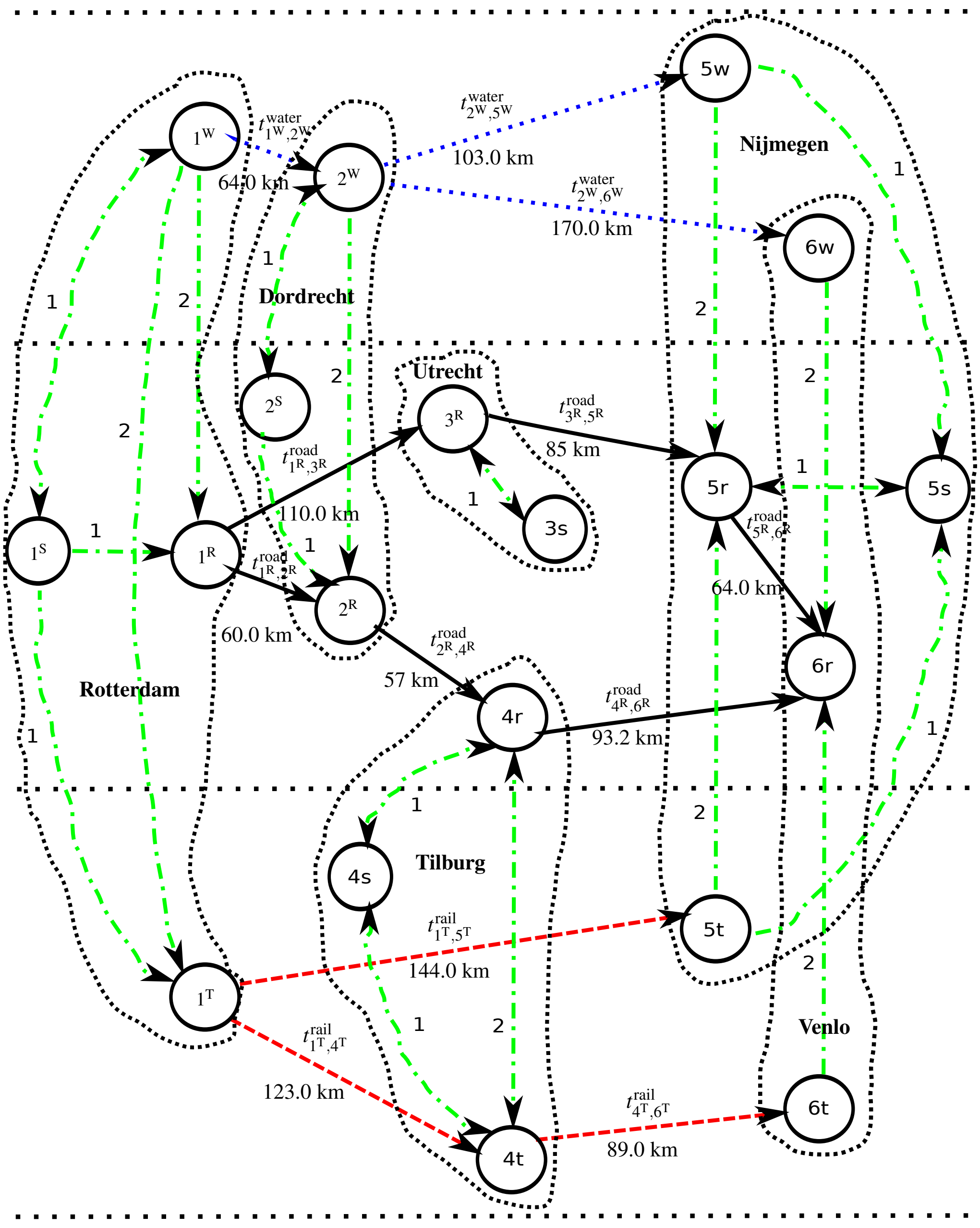

Figure 4: The corresponding IFTN model of the network shown in Figure 3. Each doubled-headed arc in the figure represents two directed links with opposite directions.

Table 1: The typical transport time $r_{i,d}$ (h). The element "–" denotes there is no transport route from its corresponding row node to its corresponding column node in the IFTN shown in Figure 3

$r_{i,d}$	1^{S}	1^{W}	1^{R}	1^{T}	2^{S}	2^{W}	2^{R}	3^{R}	3^{S}	4^{S}	4^{R}	4^{T}	5^{W}	5^{R}	5^{T}	5^{S}	6^{W}	6^{R}	6^{T}
1^{S}	0	1	1	1	8	6	3	4	6	8	6	6	14	10	6	10	18	15	10
1^{W}	1	0	1	1	6	4	4	4	6	9	7	6	12	10	6	10	16	14	10
1^{R}	–	–	0	–	–	–	1	2	4	5	3	5	–	5	–	7	–	9	9
1^{T}	–	–	–	0	–	–	–	–	–	6	6	4	–	6	4	6	–	9	8
2^{S}	–	–	–	–	0	1	3	–	–	7	5	7	9	11	–	–	13	14	11
2^{W}	–	–	–	–	1	0	1	–	–	5	3	5	7	9	–	12	11	12	9
2^{R}	–	–	–	–	–	–	0	–	–	3	1	3	–	–	–	–	–	7	7
3^{R}	–	–	–	–	–	–	–	0	1	–	–	–	–	2	–	4	–	4	–
3^{S}	–	–	–	–	–	–	–	1	0	–	–	–	–	4	–	6	–	6	–
4^{S}	–	–	–	–	–	–	–	–	–	0	1	1	–	–	–	–	–	6	5
4^{R}	–	–	–	–	–	–	–	–	–	1	0	1	–	–	–	–	–	5	5
4^{T}	–	–	–	–	–	–	–	–	–	1	1	0	–	–	–	–	–	5	3
5^{W}	–	–	–	–	–	–	–	–	–	–	–	–	0	1	–	1	–	3	–
5^{R}	–	–	–	–	–	–	–	–	–	–	–	–	–	0	–	1	–	1	–
5^{T}	–	–	–	–	–	–	–	–	–	–	–	–	–	1	0	1	–	3	–
5^{S}	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	0	–	3	–
6^{W}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	1	–
6^{R}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0	–
6^{T}	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	0

Table 2: Densities of other traffic flows on the freeway links and transport demand

Period (h)	0 – 3	3 – 9	9 – 15	15 – 21	22 – 34
$\rho^{\text{road,oth}}_{1^{R},2^{R}}, \rho^{\text{road,oth}}_{1^{R},3^{R}}, \rho^{\text{road,oth}}_{2^{R},4^{R}}$ (veh/km/lane)	45.0	65.0	45.0	25.0	20.0
$\rho^{\text{road,oth}}_{3^{R},5^{R}}, \rho^{\text{road,oth}}_{5^{R},6^{R}}, \rho^{\text{road,oth}}_{4^{R},6^{R}}$ (veh/km/lane)	20.0	65.0	25.0	45.0	20.0
$d_{1^{W},6^{R}}$ (TEU/h)	30	100	65	30	0

5.2. *All-or-nothing approach vs the RIFC approach*

This section implements two intermodal container transport planning approaches: the all-or-nothing approach and the RIFC approach. The all-or-nothing approach summarized in Section 2.3 is greedy but typically adopted in practical intermodal freight transport planning. For comparison, the all-or-nothing approach is first applied and the resulting planning performance, i.e., total delivery costs in (19), the mean and maximum computation times for single time step, and modal split rates, are presented in Table 3. The terms "AON", and "$\text{RIFC}^{\text{LP}}_{n}$" denote the all-or-nothing approach and the receding horizon intermodal container flow control approach with a prediction horizon of n time steps. The total delivery cost defined in (19) and the penalty cost on unfinished transport demands inside the IFTN are "$J(\cdot)$" and "penalty", respectively. The all-or-nothing approach leads to the largest total delivery cost (i.e., 5.40×10^{5} €) in comparison to the RIFC approach with different prediction horizons, but only takes a very few time to implement in the simulation.

The RIFC approach is implemented by using the simplex method in the CPLEX Toolbox for solving linear programming problems at each time step of the RIFC problem (29)–(33). In the simulation study, the system disturbances (i.e., transport demands, and traffic conditions on the network) within the prediction horizon $\left[k \cdot T_{\text{s}}, \left(k+N_{\text{p}}\right) \cdot T_{\text{s}}\right)$ (h) at time $k \cdot T_{\text{s}}$ are assumed to be predicted accurately. The corresponding planning performance of the RIFC approach with different prediction horizons N_{p} is shown in Table 3. It is clear from Table 3 that the total delivery

Table 3: Comparison of results of two intermodal freight transport planning approaches

	$J(\cdot)$ (€)	$t_{\mathrm{cpu}}^{\max}$ (ms)	$t_{\mathrm{cpu}}^{\mathrm{mean}}$ (ms)	truck (%)	train (%)	barge (%)	penalty (€)
AON	5.40×10^5	≤ 15.0	≤ 15.0	68.25	31.75	0.0	2.38×10^4
$\mathrm{RIFC}_5^{\mathrm{LP}}$	4.93×10^5	48.6	32.0	87.30	12.70	0.0	0.15×10^4
$\mathrm{RIFC}_{10}^{\mathrm{LP}}$	4.43×10^5	111.9	68.4	59.13	20.24	20.63	0.75×10^3
$\mathrm{RIFC}_{12}^{\mathrm{LP}}$	4.31×10^5	127.1	85.1	74.60	15.08	10.32	0.75×10^3
$\mathrm{RIFC}_{14}^{\mathrm{LP}}$	4.31×10^5	151.6	119.3	74.60	15.08	10.32	0.75×10^3

cost resulting from the RIFC approach gets smaller when the prediction horizon N_{p} increases, and it will reach a stable value when N_{p} is large enough. In this particular case, the RIFC approach with a prediction horizon of $N_{\mathrm{p}} = 12$ obtains a 20.18% reduction of the total delivery cost compared with the all-or-nothing approach. Meanwhile, Table 3 also shows that a larger N_{p} in the RIFC approach will require more computation time. This is because that the increase of N_{p} will rise the number of optimization variables and constraints in the linear optimization problem to be solved at each time step. In this simulation study, modal split rates as given in Table 3 and Table 4 are calculated for intermodal terminal 1. Essentially, the modal split rates brought by the RIFC approach are determined by the planning problem setting and the parameter selection, e.g., the length of the prediction horizon. Drawing a general statement on the change of modal split rates might be difficult. But roughly speaking, a longer prediction horizon will provide more possibilities to efficiently use trucks, trains and barges, and consequently to reduce the total delivery cost.

5.3. *Demand scenario analysis*

Transport demands may vary a lot under different situations, e.g., normal seasons or holiday seasons, working days or weekends, and early mornings or mid-afternoon. Therefore, an efficient container flow control approach should be able to obtain good planning performance in a consistent way under different demand scenarios in intermodal freight transport. In this section, five demand scenarios are constructed, i.e., a constant volume of 60 (TEU/h) during the period $[0, 18]$ (h), a peak (as defined in Table 2 and taken as the reference scenario), half volume, double volume, and triple volume with respect to the reference scenario. The RIFC approach with a prediction horizon of $N_{\mathrm{p}} = 12$ time steps is applied for controlling intermodal container flows under these five demand scenarios.

In Table 4 the terms "$\mathrm{RIFC}_{\mathrm{scenario}}^{\mathrm{LP}}$" denote the receding horizon intermodal container flow control approach for five demand scenarios, i.e., constant volume, a peak volume, half volume, double volume, and triple volume. The planning performance in this table is calculated in the same way as that in Table 3. As demonstrated in Table 4, the variations in the transport demand have a minimal impact on the implementation of the RIFC approach since roughly the same mean computation time for each single time step, $t_{\mathrm{cpu}}^{\mathrm{mean}}$, is needed by the RIFC approach under five demand scenarios. Moreover, the increase in transport demand might enlarge the mode split rates of trains and barges since capacity constraints on different modalities need to be satisfied in the RIFC approach.

5.4. *Prediction error analysis*

The prediction of system disturbances (i.e., transport demands, and traffic conditions in the network) within the current prediction horizon could involve errors. This section takes the intermodal freight transport planning problem setting defined in Section 5.1, and adopts the proposed RIFC approach for controlling container flows. The RIFC approach uses a prediction

Table 4: Analysis of transport planning performances under four demand scenarios.

	$J(\cdot)$ (€)	$t_{\mathrm{cpu}}^{\mathrm{max}}$ (ms)	$t_{\mathrm{cpu}}^{\mathrm{mean}}$ (ms)	truck (%)	train (%)	barge (%)	penalty (€)
$\mathrm{RIFC}_{\mathrm{constant}}^{\mathrm{LP}}$	4.28×10^{5}	100.3	84.5	71.43	19.05	9.52	0.15×10^{4}
$\mathrm{RIFC}_{\mathrm{reference}}^{\mathrm{LP}}$	4.31×10^{5}	127.1	85.1	74.60	15.08	10.32	0.75×10^{3}
$\mathrm{RIFC}_{\mathrm{half}}^{\mathrm{LP}}$	2.15×10^{5}	95.3	84.5	74.60	15.08	10.32	0.38×10^{3}
$\mathrm{RIFC}_{\mathrm{double}}^{\mathrm{LP}}$	8.52×10^{5}	98.0	85.6	62.70	20.63	16.67	0.15×10^{4}
$\mathrm{RIFC}_{\mathrm{triple}}^{\mathrm{LP}}$	1.40×10^{6}	93.6	83.1	64.68	20.63	14.68	0.23×10^{4}

horizon of $N_{\mathrm{p}} = 12$. This section examines the effects of prediction errors under two demand scenarios and assumes that within a prediction horizon $\left[k \cdot T_{\mathrm{s}}, \left(k+N_{\mathrm{p}}\right) \cdot T_{\mathrm{s}}\right)$ (h) accurate predictions of system disturbances at time step k are available while the predictions for the period $\left[(k+1) \cdot T_{\mathrm{s}}, \left(k+N_{\mathrm{p}}\right) \cdot T_{\mathrm{s}}\right)$ (h) may contain errors. The two real scenarios consider the transport demand information and the densities of other traffic on the freeway links for the reference scenario and the triple volume scenario given in Table 2 as the nominal values. The three prediction error levels are defined as 5%, 10%, and 15%. The prediction errors in the transport demand and densities of other traffic on the freeway links are then uniformly distributed random variables with zero mean and a standard deviation equal to respectively 5%, 10%, and 15% times the nominal value.

For each prediction error level, we run the closed-loop simulation 20 times and report the mean value, and the standard deviation of the total delivery cost $J_{\mathrm{mean}}(\cdot)$, and $J_{\mathrm{std}}(\cdot)$, and of the maximum and mean CPU times for the entire simulation, $t_{\mathrm{cpu,mean}}^{\mathrm{max}}$, $t_{\mathrm{cpu,std}}^{\mathrm{max}}$, $t_{\mathrm{cpu,mean}}^{\mathrm{mean}}$, and $t_{\mathrm{cpu,std}}^{\mathrm{mean}}$, respectively. The transport planning performance under two real demand scenarios with the four prediction error levels is presented in Table 5. The terms "$\mathrm{RIFC}_{\mathrm{demand,level}}^{\mathrm{LP}}$" correspond to the receding horizon intermodal container flow control approach under the reference demand scenario and the triple volume demand scenario with different prediction error levels. The planning performance in this table is calculated in the same way as that in Table 3. As given in Table 5, the proposed RIFC approach performs closed-loop control and deals with the existence of errors in the prediction of system disturbances. The presence of prediction errors turns out to be a very small effect on the mean value of the total delivery cost for both the reference demand scenario and the triple volume demand scenario while the effect on the standard deviation of the total delivery cost increases for the triple volume demand scenario. In particular, for the case of a 10% prediction error level for the triple volume demand scenario the standard deviation of the total delivery cost obtained by the RIFC approach reaches 0.24% of its mean value. Moreover, the existence of prediction errors also influences the maximum and mean CPU times required by the RIFC approach. The influences on $t_{\mathrm{cpu,mean}}^{\mathrm{mean}}$ are more perceptible for the triple volume demand scenario than for the reference demand scenario. It is expected that prediction errors could change the activation of the constraints in the optimization problem (29)–(33), and thus influence the computation time. Roughly speaking, under high-volume demand scenarios the presence of prediction errors has a bigger effect on guaranteeing the satisfaction of these constraints, and consequently has a larger influence on the computation time and planning performance of the RIFC approach.

6. Conclusions and future work

This paper investigates intermodal freight transport planning problems among deep-sea terminals and inland terminals in hinterland haulage for a horizontally fully integrated intermodal

Table 5: Analysis of transport planning performances under four prediction error levels.

	$J_{\text{mean}}(\cdot)$ (€)	$J_{\text{std}}(\cdot)$ (€)	$t_{\text{cpu,mean}}^{\text{max}}$ (ms)	$t_{\text{cpu,std}}^{\text{max}}$ (ms)	$t_{\text{cpu,mean}}^{\text{mean}}$ (ms)	$t_{\text{cpu,std}}^{\text{mean}}$ (ms)
$\text{RIFC}_{\text{reference,real}}^{\text{LP}}$	4.31×10^5	–	127.1	–	85.1	–
$\text{RIFC}_{\text{reference,5\%}}^{\text{LP}}$	4.31×10^5	0.0	99.1	8.9	84.2	2.0
$\text{RIFC}_{\text{reference,10\%}}^{\text{LP}}$	4.31×10^5	0.0	106.4	8.8	86.0	1.4
$\text{RIFC}_{\text{reference,15\%}}^{\text{LP}}$	4.31×10^5	0.0	122.1	26.2	87.5	3.2
$\text{RIFC}_{\text{triple,real}}^{\text{LP}}$	1.40×10^6	–	93.6	–	83.1	–
$\text{RIFC}_{\text{triple,5\%}}^{\text{LP}}$	1.40×10^6	1.45×10^3	137.8	26.7	91.2	2.9
$\text{RIFC}_{\text{triple,10\%}}^{\text{LP}}$	1.40×10^6	3.33×10^3	116.0	22.2	91.3	3.1
$\text{RIFC}_{\text{triple,15\%}}^{\text{LP}}$	1.40×10^6	2.30×10^3	122.8	14.7	93.4	1.9

freight transport operator. The behavior of an intermodal freight transport network (IFTN) is formulated from an aggregated container flow perspective and capture network characteristics, such as modality changes at intermodal terminals, capacities of physical infrastructures, time-dependent transport times on freeways, and time schedules for trains and barges. This paper proposes a receding horizon intermodal container flow control (RIFC) approach to address dynamic transport demands and traffic conditions in the network for intermodal freight transport planning problems. This container flow control approach leads to a linear programming problem. Therefore, the developed network modeling approach and the proposed container flow control approach are capable of being applied to large-sized networks. With an appropriate choice of the prediction horizon the proposed RIFC approach outperforms a greedy all-or-nothing approach in terms of the total delivery cost in the simulation study. Different demand scenarios and different prediction error levels on transport demands and traffic conditions in the IFTN are also examined by conducing simulation experiments.

Below some directions are given for future research. Environmental issues, e.g., reducing CO_2 emission, receive increasing attentions in intermodal freight transport. Although the IFTN model proposed in this paper can capture the environmental issues with a generic term, i.e., "transport cost", it is still useful to explicitly capture environmental issues in the network model and the planning objective function. In addition, multiple intermodal freight transport operators might be involved in the freight delivery process due to either organizational or commercial reasons. Therefore, cooperative intermodal container flow control methods need to be investigated such that the overall delivery cost is minimized while considering the interests of each individual intermodal freight transport operator.

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References

Alessandri, A., Cervellera, C., Cuneo, M., Gaggero, M., Soncin, G., 2008. Modeling and feedback control for resource allocation and performance analysis in container terminals. IEEE Transactions on Intelligent Transportation Systems 9, 601–614.

Alessandri, A., Sacone, S., Siri, S., 2007. Modelling and optimal receding-horizon control of maritime container terminals. Journal of Mathematical Modelling and Algorithms 6, 109–133.

Assad, A., 1980. Models for rail transportation. Transportation Research Part A: General 14, 205–220.

Ayed, H., Habas, Z., Khadraoui, D., Galvez-Fernandez, C., 2011. A parallel algorithm for solving time dependent multimodal transport problem, in: Proceedings of the 14th International IEEE Conference on Intelligent Transportation Systems (ITSC 2011), Washington, DC, USA. pp. 722–727.

Barnhart, C., Ratliff, H., 1993. Modeling intermodal routing. Journal of Business Logistics 14, 205–223.

Boardman, B., Malstrom, E., Butler, D., Cole, M., 1997. Computer assisted routing of intermodal shipments. Computers and Industrial Engineering 33, 311–314.

Caris, A., Macharis, C., Janssens, G., 2008. Planning problems in intermodal freight transport: Accomplishments and prospects. Transportation Planning and Technology 31, 277–302.

Caris, A., Macharis, C., Janssens, G., 2013. Decision support in intermodal transport: A new research agenda. Computers in Industry 64, 105–112.

Cassidy, M., Jang, K., Daganzo, C., 2011. Macroscopic fundamental diagrams for freeway networks: Theory and observation. Transportation Research Record 2260, 8–15.

Chang, T.S., 2008. Best routes selection in international intermodal networks. Computers and Operations Research 35, 2877–2891.

Cho, J., Kim, H., Choi, H., 2012. An intermodal transport network planning algorithm using dynamic programming - A case study: From Busan to Rotterdam in intermodal freight routing. Applied Intelligence 36, 529–541.

Chow, A., 2013. Generalized network fundamental diagram for motorway traffic management, in: Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013), The Hague, The Netherlands. pp. 1016–1021.

Crainic, T., Ferland, J.A., Rousseau, J.M., 1984. Tactical planning model for rail freight transportation. Transportation Science 18, 165–184.

Crainic, T., Kim, K., 2007. Intermodal transportation, in: Barnhart, C., Laporte, G. (Eds.), Transportation. Elsevier. volume 14 of *Handbooks in Operations Research and Management Science*. chapter 8, pp. 467–537.

Daganzo, C., 2007. Urban gridlock: Macroscopic modeling and mitigation approaches. Transportation Research Part B: Methodological 41, 49–62.

Daganzo, C., Geroliminis, N., 2008. An analytical approximation for the macroscopic fundamental diagram of urban traffic. Transportation Research Part B: Methodological 42, 771–781.

Daganzo, C.F., 1997. Fundementals of Transportation and Traffic Operations. Pergamon.

Daggett, S., 1955. Principles of Inland Transportation. 4th ed., Harper & Brothers, New York, USA.

de Dios Ortúzar, J., Willumsen, L.G., 2011. Modelling Transport. 4th ed., Wiley, UK.

van den Driest, M., 2010. Reducing CO2-emission of container transport in the Netherlands. MSc thesis, Delft University of Technology, Delft, The Netherlands.

Geroliminis, N., Daganzo, C., 2008. Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings. Transportation Research Part B: Methodological 42, 759–770.

Geroliminis, N., Sun, J., 2011a. Hysteresis phenomena of a macroscopic fundamental diagram in freeway networks. Transportation Research Part A: Policy and Practice 45, 966–979.

Geroliminis, N., Sun, J., 2011b. Properties of a well-defined macroscopic fundamental diagram for urban traffic. Transportation Research Part B: Methodological 45, 605–617.

Grasman, S.E., 2006. Dynamic approach to stratigic and operational multimodal routing decisions. International Journal of Logistics Systems and Management 2, 96–106.

Haddad, J., Ramezani, M., Geroliminis, N., 2013. Cooperative traffic control of a mixed network with two urban regions and a freeway. Transportation Research Part B: Methodological 54, 17–36.

Hegyi, A., De Schutter, B., Hellendoorn, H., 2005. Model predictive control for optimal coordination of ramp metering and variable speed limits. Transportation Research Part C: Emerging Technologies 13, 185 – 209.

Jarzemskiene, I., 2007. The evolution of intermodal transport research and its development issues. Transport 22, 296–306.

Jourquin, B., 2006. A multi-flow multi-modal assignment procedure on large freight transportation networks. Studies in Regional Science 35, 929–945.

Kotsialos, A., Papageorgiou, M., Mangeas, M., Haj-Salem, H., 2002. Coordinated and integrated control of motorway networks via non-linear optimal control. Transportation Research Part C: Emerging Technologies 10, 65–84.

Li, L., Negenborn, R.R., De Schutter, B., 2013. A sequential linear programming approach for flow assignment in intermodal freight transport, in: Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013), The Hague, The Netherlands. pp. 1124–1230.

Li, L., Negenborn, R.R., De Schutter, B., 2014. Receding horizon approach for container flow assignment in intermodal freight transport. Transportation Research Record 2410, 132–140.

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

Maciejowski, J., 2002. Predictive control with constraints. Prentice-Hall, Harlow, UK.

Maia, L.C., do Couto, A.F., 2013. An innovative freight traffic assignment model for multimodal networks. Computers

in Industry 64, 121–127.
Mc Namara, P., Negenborn, R.R., De Schutter, B., Lightbody, G., 2013. Optimal coordination of a multiple HVDC link system using centralized and distributed control. IEEE Transactions on Control Systems Technology 21, 302–314.
Meng, Q., Wang, S., Andersson, H., Thun, K., 2014. Containership routing and scheduling in liner shipping: Overview and future research directions. Transportation Science 48, 265–280.
Nabais, J.L., Negenborn, R.R., Ayala Botto, M., 2013a. Hierarchical model predictive control for optimizing intermodal container terminal operations, in: Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013), The Hague, The Netherlands. pp. 708–713.
Nabais, J.L., Negenborn, R.R., Benitez, R., Ayala Botto, M., 2013b. A constrained MPC heuristic to achieve a desired transport modal split at intermodal hubs, in: Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013), The Hague, The Netherlands. pp. 714–719.
Negenborn, R.R., 2007. Multi-agent model predictive control with applications to power networks. Ph.D thesis, Delft University of Technology, Delft, The Netherlands.
Negenborn, R.R., van Overloop, P.J., Keviczky, T., De Schutter, B., 2009. Distributed model predictive control of irrigation canals. Networks and Heterogeneous Media 4, 359–380.
van Overloop, P.J., Negenborn, R.R., De Schutter, B., van de Giesen, N., 2010. Predictive control for national water flow optimization in the netherlands, in: Negenborn, R.R., Lukszo, Z., Hellendoorn, H. (Eds.), Intelligent Infrastructures. Springer Netherlands. volume 42 of *Intelligent Systems, Control and Automation: Science and Engineering*. chapter 17, pp. 439–461.
Pachl, J., 2009. Railway Operation and Control. 2nd ed., VTD Rail Publishing, USA.
Pardalos, P., Resende, M. (Eds.), 2002. Handbook of Applied Optimization. Oxford University Press, Oxford, UK.
Peeta, S., Ziliaskopoulos, A., 2001. Foundations of dynamic traffic assignment: The past, the present and the future. Networks and Spatial Economics 1, 233–265.
Psaraftis, H.N., Kontovas, C.A., 2013. Speed models for energy-efficient maritime transportation: A taxonomy and survey. Transportation Research Part C: Emerging Technologies 26, 331–351.
Rawlings, J., Mayne, D., 2009. Model Predictive Control: Theory and Design. Nob Hill, Madison, WI.
del Real, A., Arce, A., Bordons, C., 2014. An integrated framework for distributed model predictive control of large-scale power networks. IEEE Transactions on Industrial Informatics 10, 197–209.
van Riessen, B., Negenborn, R.R., Dekker, R., Lodewijks, G., 2015. Service network design for an intermodal container network with flexible transit times and the possibility of using subcontracted transport. International Journal of Shipping and Transport Logistics 7, 457–478.
Sarimveis, H., Patrinos, P., Tarantilis, C., Kiranoudis, C., 2008. Dynamic modeling and control of supply chain systems: A review. Computers and Operations Research 35, 3530–3561.
SteadieSeifi, M., Dellaert, N., Nuijten, W., Woensel, T.V., Raoufi, R., 2014. Multimodal freight transportation planning: A literature review. European Journal of Operational Research 233, 1–15.
Sys, C., Vanelslander, T. (Eds.), 2011. Future Challenges for inland Navigation - A scientific appraisal of the consequences of possible strategic and economic developments up to 2030. UPA, Belgium.
Wang, W., Rivera, D., 2008. Model predictive control for tactical decision-making in semiconductor manufacturing supply chain management. IEEE Transactions on Control Systems Technology 16, 841–855.
Xin, J., Negenborn, R.R., Lodewijks, G., 2013. Hybrid MPC for balancing throughput and energy consumption in an automated container terminal, in: Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013), The Hague, The Netherlands. pp. 1238–1244.
Yperman, I., 2007. The Link Transmission Model for Dynamic Network Loading. Ph.D thesis, Katholieke Universiteit Leuven, Leuven, Belgium.
Ziliaskopoulos, A., Wardell, W., 2000. An intermodal optimum path algorithm for multimodal networks with dynamic arc travel times and switching delays. European Journal of Operational Research 125, 486–502.