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A Receding Horizon Approach for Container Flow Assignment in Intermodal Freight Transport

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ABSTRACT

Hinterland haulage among major deep-sea ports and the cargos' inland origins/destinations has become an important component in modern logistic systems. Intermodal freight transport integrates the use of different modalities (e.g., trucks, trains, barges.) during the freight delivery process to improve the reliability and efficiency of hinterland haulage. In this paper, we first introduce intermodal freight transport and present existing intermodal container (freight) transport planning approaches. Next, a dynamic intermodal transport network (ITN) model developed by the authors in an earlier work is briefly recapitulated. To deal with the dynamic transport demand and the dynamic traffic conditions in the ITN, we propose a so-called receding horizon approach to address the intermodal container flow assignment problem between deep-sea terminals and inland terminals in hinterland cargo transport. The proposed approach considers the movement of containers as a flow and makes container flow assignment decisions in a receding horizon fashion during the container transport process. At each time step of the process, the future behavior of the ITN is predicted using a dynamic ITN model with load-dependent freeway transport times fed with information on the current and estimated transport demands and traffic conditions. To determine container assignments using this model, a nonlinear optimization problem is solved at each time step. Simulation studies for intermodal container flow assignments are conducted using both an all-or-nothing approach and the proposed receding horizon approach.

1 INTRODUCTION

In modern logistic systems, hinterland haulage among major deep-sea ports and the inland origins/ destinations of the cargos has become an important component of the intermodal transport chain. Organizing the hinterland haulage in a reliable and efficient way will increase the profits of freight forwarders, strengthen the competitiveness of deep-sea ports, and provide benefits to the supply chain management of corporations. However, as cargo transport demands continuously increase in deep-sea ports, hinterland haulage is frequently encountering challenges due to the shortage of physical transport capacities, the inefficiency of transport organization, etc. (*1*). Intermodal freight transport is considered to be an effective way to address the challenges mentioned above and therefore has been getting more and more attention from different stakeholders in hinterland haulage, e.g., port operators, terminal operators, freight forwarders (*1, 2*), and scientific researchers in transport and logistics (*3–8*).

The United Nations Economic Commission for Europe defines intermodal freight transport as "the movement of goods in one and the same loading unit by successive modes of transport without handling of the goods themselves when changing modes" (*4*). Intermodal freight transport integrates the use of different modalities (e.g., trucks, trains, barges) during the freight delivery process to improve the reliability and efficiency of hinterland haulage. In the field of intermodal freight transport, the above mentioned challenges are investigated at different decision-making levels: the investment of new transport infrastructures at the strategic level, the transport service network design at the tactical level, and the freight flow assignment at the operational level. The review papers by Macharis and Bontekoning (*5*), Jarzemskiene (*6*), and Caris et al. (*7, 8*) provide a detailed literature survey of research in intermodal freight transport. In this paper, we focus on investigating intermodal container (freight) flow assignment problems among deep-sea terminals and inland terminals in the hinterland faced by intermodal freight forwarders at the operational level.

Intermodal freight transport planning addresses two basic issues: intermodal routing and intermodal container assignment. Intermodal routing involves the selection of routes for shipments through an intermodal transport network (ITN). The intermodal routing methods can be categorized into two main directions: the shortest path based methods and the dynamic programming based methods. A number of intermodal routing methods have been developed on the basis of the shortest path algorithm and its different variants, e.g., a shortest path procedure (*9*), a K-shortest path algorithm (*10*), a time-dependent intermodal optimum path algorithm (*11*), a heuristic algorithm based on relaxation and decomposition techniques (*12*), and a parallel algorithm for computing a global shortest path solution based on the decomposition of the transport network (*13*). For the dynamic programming based methods, Grasman (*14*) derived dynamic programming formulations of an intermodal routing problem and solved the problem with Dijkstra's algorithm. Cho et al. (*15*) presented a dynamic programming algorithm applying a label setting algorithm together with pruning rules to solve weighted constrained shortest path problems of international container transport for both imports and exports.

Intermodal container assignment determines how much volume of the transport demand will be assigned to each of the candidate routes in order to deliver a transport demand from its origin node to its destination node over an ITN. These candidate routes are the outcome of intermodal routing methods (*8*). When considering unlimited capacities of transport connections, in practice typically an all-or-nothing approach is adopted to assign the transport demand. That is, the entire volume of the transport demand will be assigned to the route that leads to the minimum value of the user-supplied objective function given by intermodal freight forwarders. In practice, the transport demand and the traffic conditions in the network show dynamic behavior, e.g., unexpected transport order requests, transport order cancellations, the evolution of the transport times on freeway links, etc. These dynamic behaviors cannot be estimated with a high precision for a long time period. In this paper, we study intermodal freight transport problems from a system and control perspective by considering dynamic ITN models and determining intermodal routing and intermodal container assignment by solving an optimization problem. We propose a so-called receding horizon intermodal container flow assignment approach that uses a dynamic ITN model based on the authors' earlier work (*16*). The intermodal container flow assignments are updated in a receding horizon way to address the dynamic changes of the transport demand and the traffic conditions. The dynamic ITN model allows the prediction of the network behavior based on information on the current and estimated future transport demands and traffic conditions. The predicted network behavior information benefits the decision-making of freight forwarders and enables container flows being assigned in a way such that unexpected transport situations (e.g., road congestion, overlong delays, etc.) are partially or even completely avoided.

The paper is structured as follows. A brief recapitulation of the dynamic ITN model developed by the authors in an earlier work (*16*) is presented in Section 2. A receding horizon intermodal container flow assignment approach is proposed for the case of the ITN with dynamic transport demands and dynamic traffic conditions in Section 3. Simulation studies are conducted to show the advantages of the proposed receding horizon approach in Section 4. Conclusions and directions for future research are given in Section 5.

2 INTERMODAL TRANSPORT NETWORK MODEL

A dynamic ITN model was formulated for the load-dependent travel time on freeways connections of the network in our earlier work (*16*). The proposed receding horizon container flow assignment approach will be implemented using this model. Therefore, in this section we present a brief recapitulation of the dynamic ITN model used in (*16*).

2.1 Dynamics of the ITN

An ITN can be represented as a directed graph $\mathscr{G}(\mathscr{V},\mathscr{E},\mathscr{M})$. The node set $\mathscr{V}=\mathscr{V}_{\text{truck}}\cup\mathscr{V}_{\text{train}}\cup\mathscr{V}_{\text{barge}}\cup\mathscr{V}_{\text{store}}$ is a finite nonempty set, in which the storage node set $\mathscr{V}_{\text{store}}$ represents storage yards shared by different single-mode terminals inside each intermodal terminal of the network. The sets $\mathscr{V}_{\text{truck}}$, $\mathscr{V}_{\text{train}}$, and $\mathscr{V}_{\text{barge}}$ represent truck terminals, train terminals, and barge terminals inside each intermodal terminal of the network, respectively. The set $\mathscr{M}=\mathscr{M}_1\cup\mathscr{M}_2$ represents transport modes and mode transfer types in the network with $\mathscr{M}_1=\{\text{truck},\text{train},\text{barge},\text{store}\}$ 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 connections among nodes. A link (i,j,m) with $i,j\in\mathscr{V}$ and $m\in\mathscr{M}$ will be denoted by $l_{i,j}^{m}$. Depending on whether a model transfer happens or not in one link, this link is categorized as transfer link or transport link, respectively. Figure 1 presents an ITN model to illustrate the elements mentioned above.

Each transport demand (o,d) in the ITN belongs to the transport demand set $\mathscr{O}_{\text{od}}\subseteq\mathscr{V}\times\mathscr{V}$. For each pair $(o,d)\in\mathscr{O}_{\text{od}}$ we denote the volume of this transport demand at time step k as $d_{o,d}(k)$. The dynamic ITN model is a discrete-time model with T_{s} (h) as the time step size. It is formulated as follows:

$$\begin{aligned} x_{i,o,d}(k+1) = {} & x_{i,o,d}(k) + \sum_{(j,m)\in\mathscr{N}_i^{\text{in}}} u_{j,i,o,d}^{m}(k)T_{\text{s}} - \sum_{(j,m)\in\mathscr{N}_i^{\text{out}}} y_{i,j,o,d}^{m}(k)T_{\text{s}} + d_{i,o,d}^{\text{in}}(k)T_{\text{s}} \\ & - d_{i,o,d}^{\text{out}}(k)T_{\text{s}}, \forall(o,d)\in\mathscr{O}_{\text{od}}, \forall i,j\in\mathscr{V}, \forall m\in\mathscr{M}, \forall k, \end{aligned} \tag{1}$$

$$q_{i,j,o,d}^{m,\text{out}}(k) = \sum_{\substack{k_e=k-t_{i,j}^{m,max} \\ k_e+t_{ij}^{m}(k_e)=k}}^{k-1} q_{i,j,o,d}^{m,in}(k_e), \forall(i,j,m)\in\mathscr{E}, \forall(o,d)\in\mathscr{O}_{\text{od}}, \forall k, \tag{2}$$

$$x_{i,j,o,d}^{m}(k+1) = x_{i,j,o,d}^{m}(k) + \left(q_{i,j,o,d}^{m,\text{in}}(k) - q_{i,j,o,d}^{m,\text{out}}(k)\right)T_{\text{s}}, \forall(i,j,m)\in\mathscr{E}, \forall(o,d)\in\mathscr{O}_{\text{od}}, \forall k, \tag{3}$$

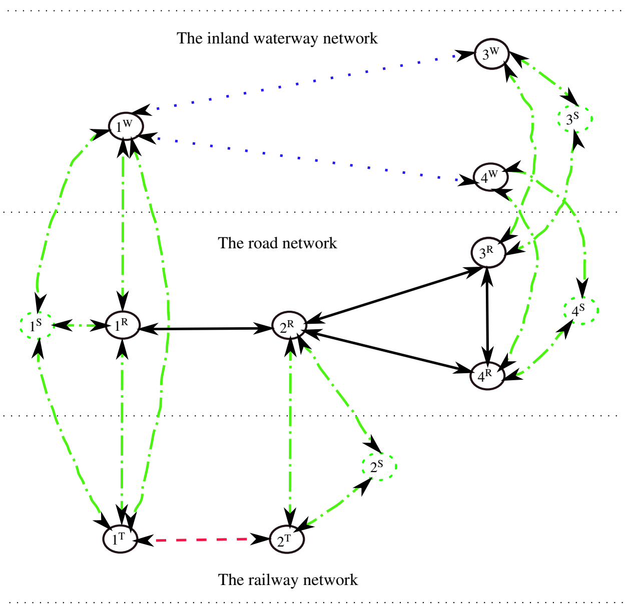

FIGURE 1 An ITN model. The nodes 1^{R}, 1^{T}, 1^{W}, and 1^{S} represent the truck terminal, the train terminal, the barge terminal and the storage yard at intermodal terminal 1, respectively. The dotted blue arcs, the solid black arcs, the dashed red arcs, and the dash-dotted green arcs indicate 4 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 three different types of transport modes (barges, trucks and trains) in nodes of the ITN, respectively. Each doubled-headed arc in the figure represents two directed links with opposite directions.

$$\rho_{i,j}^{\text{truck}}(k) = \frac{L_{\text{truck}}}{L_{\text{oth}}} \left(\sum_{(o,d)\in\mathscr{O}_{\text{od}}} \frac{1}{L_{i,j}^{\text{truck}} \lambda_{i,j}^{\text{truck}}} x_{i,j,o,d}^{\text{truck}}(k) \right) + \rho_{i,j}^{\text{truck,oth}}(k) \tag{4}$$

$$v_{i,j}^{\text{truck,truck}}(k) = v_{i,j,\text{free}}^{\text{truck,truck}} \exp\left[-\frac{1}{a_{i,j}^{\text{truck,truck}}} \left(\frac{\rho_{i,j}^{\text{truck}}(k)}{\rho_{i,j,\text{crit}}^{\text{truck}}} \right)^{a_{i,j}^{\text{truck,truck}}} \right] \tag{5}$$

$$t_{i,j}^{\text{truck}}(k) = \textbf{round}\left(\frac{L_{i,j}^{\text{truck}}}{v_{i,j}^{\text{truck,truck}}(k)} \frac{1}{T_{\text{s}}} \right), \tag{6}$$

$$q_{i,j,o,d}^{m,\text{in}}(k) = y_{i,j,o,d}^{m}(k), \forall\, i \in \mathscr{V}, \forall (j,m) \in \mathscr{N}_i^{\text{out}}, \forall (o,d) \in \mathscr{O}_{\text{od}}, \forall k, \tag{7}$$

$$u_{i,j,o,d}^{m}(k) = q_{i,j,o,d}^{m,\text{out}}(k), \forall\, i \in \mathscr{V}, \forall (j,m) \in \mathscr{N}_i^{\text{in}}, \forall (o,d) \in \mathscr{O}_{\text{od}}, \forall k, \tag{8}$$

$$\sum_{(o,d)\in\mathscr{O}_{\text{od}}} \sum_{(j,m)\in\mathscr{N}_i^{\text{in}}} u_{j,i,o,d}^{m}(k) \le h_i^{\text{in}}, \forall i \in \mathscr{V}, \forall k, \tag{9}$$

$$\sum_{(o,d)\in\mathscr{O}_{\text{od}}} x_{i,o,d}(k) \le S_i, \forall i \in \mathscr{V}, \forall k, \tag{10}$$

$$\sum_{(o,d)\in\mathcal{O}_{\rm od}}\sum_{(j,m)\in\mathcal{N}_i^{\rm out}} y_{i,j,o,d}^m(k)\le h_i^{\rm out},\forall i\in\mathcal{V},\forall k, \tag{11}$$

$$\sum_{(o,d)\in\mathcal{O}_{\rm od}} x_{i,j,o,d}^m(k)\le C_{i,j}^m,\forall (i,j,m)\in\mathcal{E},\forall k, \tag{12}$$

$$\sum_{(o,d)\in\mathcal{O}_{\rm od}} q_{i,j,o,d}^{m,\rm in}(k)\le C_{i,j}^{m,\rm in},\forall (i,j,m)\in\mathcal{E},\forall k, \tag{13}$$

where

- $x_{i,o,d}(k)$ (TEU) is the number of containers corresponding to transport demand (o,d) and staying at node i at time step k.

- $u_{j,i,o,d}^m(k)$ (TEU/h) is the container flow corresponding to transport demand (o,d) and entering node i through link $l_{j,i}^m, (j,m)\in\mathcal{N}_i^{\rm in}$ at time step k where the set $\mathcal{N}_i^{\rm in}$ is defined as

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

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

- $y_{i,j,o,d}^m(k)$ (TEU/h) is the container flow corresponding to transport demand (o,d) and leaving node i through link $l_{i,j}^m, (j,m)\in\mathcal{N}_i^{\rm out}$ at time step k where the set $\mathcal{N}_i^{\rm out}$ is defined as

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

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

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

- $d_{i,o,d}^{\rm out}(k)$ (TEU/h) is the container flow corresponding to transport demand (o,d) and arriving at the final destination node i at time step k. The value of $d_{i,o,d}^{\rm out}(k)$ equals $\sum_{(j,m)\in\mathcal{N}_i^{\rm in}} u_{j,i,o,d}^m(k)$ when $i=d$ (here, we assume that containers coming from each transport demand will immediately leave the network once they arrive at their destination), and otherwise it is zero.

- $t_{i,j}^m(k)T_{\rm s}$ (h) is the transport time on link $l_{i,j}^m$ at time step k, and is given by

$$\begin{aligned} T_{i,j}^m(k) &= t_{i,j}^m(k)T_{\rm s},\\ t_{i,j}^m(k) &\in \mathbb{N}\backslash\{0\},\\ t_{i,j}^m(k) &\le t_{i,j}^{m,\max}, \end{aligned}$$

  where $t_{i,j}^{m,\max}$ is a positive integer that corresponds to $t_{i,j}^{m,\max}T_{\rm s}$, the maximum transport time on link $l_{i,j}^m$.

- $q_{i,j,o,d}^{m,\rm out}(k)$ (TEU/h) is the container flow corresponding to transport demand (o,d) and leaving link $l_{i,j}^m$ at time step k.

- $q_{i,j,o,d}^{m,\rm in}(k)$ (TEU/h) is the container flow corresponding to transport demand (o,d) and entering link $l_{i,j}^m$ at time step k.

- $x^m_{i,j,o,d}(k)$ (TEU) is the number of containers corresponding to transport demand (o,d) and traveling in link $l^m_{i,j}$ at time step k.
- $\rho^{\text{truck,truck}}_{i,j}(k)$ is the actual traffic density corresponding to freight truck flow on link $l^{\text{truck}}_{i,j}$ at time step k.
- $\rho^{\text{truck,oth}}_{i,j}(k)$ is the traffic density induced by the other traffic on link $l^{\text{truck}}_{i,j}$ at time step k.
- L_{truck} (m) and L_{oth} (m) are the typical length of freight trucks and other vehicles, respectively.
- $L^{\text{truck}}_{i,j}$ (km) and $\lambda^{\text{truck}}_{i,j}$ are the length and the number of lanes of link $l^{\text{truck}}_{i,j}$, respectively.
- $v^{\text{truck,truck}}_{i,j}(k)$ and $t^{\text{truck}}_{i,j}(k)$ are the average speed and the average transport time of container flow on freeway link $l^{\text{truck}}_{i,j}$ at time step k, respectively.
- $v^{\text{truck,truck}}_{i,j,\text{free}}$, $a^{\text{truck,truck}}_{i,j}$ and $\rho^{\text{truck,truck}}_{i,j,\text{crit}}$ are the model parameters in the fundamental diagram model. These three model parameters have typical values as: $v^{\text{truck,truck}}_{i,j,\text{free}} = 120$ km/h, $\rho^{\text{truck,truck}}_{i,j,\text{crit}} = 33.5$ veh/km/lane, and $a^{\text{truck,truck}}_{i,j} = 1.867$ (*17, 18*).
- h^{in}_i (TEU/h) and h^{out}_i (TEU/h) are the maximal container unloading and loading rates of the equipment in node i, respectively.
- S_i (TEU) is the storage capacity in node i.
- $C^m_{i,j}$ (TEU) is the transport or transfer capacity of link $l^m_{i,j}$.
- $C^{m,\text{in}}_{i,j}$ (TEU/h) is the maximal volume of container flows that can enter link $l^m_{i,j}$ at each time step.

The dynamics of the ITN comprise the dynamics of nodes given by (1), the dynamics of links given by (2)-(6), and the dynamics of the interactions among nodes and links in the network, given by (7)-(8). There are also some capacity constraints on nodes and links, given by (9)-(13). This model captures all possible flow assignments in intermodal freight transport. A particular/optimal flow assignment can be determined by solving an optimization problem subject to the corresponding user-supplied objective function. For clarification, this paper formulates a general ITN model, in which different types of terminals are identified by the physical capacities (i.e., maximal container unloading and loading rates and the storage capacity.), the possibility of changing modality, and the availability of incoming and outgoing transport connections at their corresponding nodes.

2.2 The optimal container flow assignment problem

For intermodal container flow assignments in hinterland haulage, we choose to minimize the total transport time and the total delivery cost of transport demands in the network. The objective function is defined as follows:

$$J = \alpha(J_1 + J_2) + J_3 + J_4 \tag{14}$$

with

$$J_1 = \sum_{(o,d)\in\mathscr{O}_{\text{od}}} w_{o,d} \left[\sum_{k=1}^{N-1} \left[\sum_{i\in\mathscr{V}} x_{i,o,d}(k)T_{\text{s}} + \sum_{(i,j,m)\in\mathscr{E}} x^m_{i,j,o,d}(k)T_{\text{s}} \right] \right] \tag{15}$$

$$J_2 = \sum_{(o,d)\in\mathscr{O}_{\mathrm{od}}} w_{o,d}\left[\sum_{i\in\mathscr{V}} x_{i,o,d}(N) r_{i,d} + \sum_{(i,j,m)\in\mathscr{E}} x^m_{i,j,o,d}(N) r^{m,d}_{i,j}\right] \tag{16}$$

$$J_3 = \sum_{(o,d)\in\mathscr{O}_{\mathrm{od}}} w_{o,d}\left[\sum_{k=1}^{N-1}\left[\sum_{i\in\mathscr{V}} x_{i,o,d}(k) T_{\mathrm{s}} C_{i,\mathrm{store}}(k) + \sum_{(i,j,m)\in\mathscr{E}} x^m_{i,j,o,d}(k) T_{\mathrm{s}} C^m_{i,j,\mathrm{tran}}(k)\right]\right] \tag{17}$$

$$J_4 = \sum_{(o,d)\in\mathscr{O}_{\mathrm{od}}} w_{o,d}\left[\sum_{i\in\mathscr{V}} x_{i,o,d}(N) c_{i,d} + \sum_{(i,j,m)\in\mathscr{E}} x^m_{i,j,o,d}(N) c^{m,d}_{i,j}\right], \tag{18}$$

where

- J_1, J_3 are the total transport time and the total delivery cost of transport demands $\mathscr{O}_{\mathrm{od}}$ 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 $\sum_{(o,d)\in\mathscr{O}_{\mathrm{od}}} w_{o,d} = 1$ always holds.

- $C_{i,\mathrm{store}}(k)$ (€/TEU/h) is the cost associated with storing containers in the node i at time step k.

- $C^m_{i,j,\mathrm{tran}}(k)$ (€/TEU/h) is the transport or transfer cost, i.e., the cost that has to be paid for the use of a link to transport or transfer containers at time step k.

- $r_{i,d}$ (h/TEU) and $c_{i,d}$ (€/TEU) are the typical[2] transport time and the typical delivery cost for containers being transported from node i to destination node d, respectively.

- $r^{m,d}_{i,j}$ (h/TEU) and $c^{m,d}_{i,j}$ (€/TEU) are the typical[3] transport time and the typical delivery cost for containers being transported from link $l^m_{i,j}$ to destination node d, respectively.

- α (€/h) is the conversion factor for converting transport times to the equivalent monetary cost.

- $N \cdot T_{\mathrm{s}}$ (h) is the planning horizon with $N \in \mathbb{N}\backslash\{0\}$. In the receding horizon intermodal container flow assignment approach in Section 3, N_{sim} is the step length of the whole simulation; N_{pred} is the step length of the prediction horizon at each simulation step, respectively.

Therefore, the optimal container flow assignment problem can be formulated as the following nonlinear optimization problem:

$$\min_{\tilde{\mathbf{x}}_1,\tilde{\mathbf{x}}_2,\tilde{\mathbf{y}},\tilde{\mathbf{u}},\tilde{\rho}} J(\tilde{\mathbf{x}}_1,\tilde{\mathbf{x}}_2,\tilde{\mathbf{y}},\tilde{\mathbf{u}},\tilde{\rho},\tilde{t}) \tag{19}$$

$$\text{subject to} \qquad (1)-(13).$$

where

- $\tilde{\mathbf{x}}_1$ contains all $x_{i,o,d}(k)$, for $i \in \mathscr{V}, (o,d) \in \mathscr{O}_{\mathrm{od}}, k = 1,\ldots,N$,

- $\tilde{\mathbf{x}}_2$ contains all $x^m_{i,j,o,d}(k)$, for $(i,j,m) \in \mathscr{E}, (o,d) \in \mathscr{O}_{\mathrm{od}}, k = 1,\ldots,N$,

- $\tilde{\mathbf{y}}$ contains all $y^m_{i,j,o,d}(k)$, for $i \in \mathscr{V}, (j,m) \in \mathscr{N}^{\mathrm{out}}_i, (o,d) \in \mathscr{O}_{\mathrm{od}}, k = 1,\ldots,N$,

- $\tilde{\mathbf{u}}$ contains all $u^m_{j,i,o,d}(k)$, for $i \in \mathscr{V}, (j,m) \in \mathscr{N}^{\mathrm{in}}_i, (o,d) \in \mathscr{O}_{\mathrm{od}}, k = 1,\ldots,N$,

[2]The values of $r_{i,d}$ and $c_{i,d}$ can be obtained from statistical data.
[3]The values of $r^{m,d}_{i,j}$ and $c^{m,d}_{i,j}$ can be obtained from statistical data.

- $\tilde{\rho}$ contains all $\rho_{i,j}^{\text{truck}}(k)$ for $\{i,j,\text{truck}\} \in \mathscr{E}, k = 1,\cdots,N$,
- $\tilde{t}$ contains all $t_{i,j}^{\text{truck}}(k)$ for $\{i,j,\text{truck}\} \in \mathscr{E}, k = 1,\cdots,N$,

Because of the existence of the nonlinear equations (5) and (6), the optimal container flow assignment problem is a nonlinear optimization problem. The Optimization Toolbox in MATLAB is used to solve the optimal container flow assignment problem.

3 A RECEDING HORIZON CONTAINER FLOW ASSIGNMENT APPROACH

In this section, a so-called receding horizon intermodal container flow assignment approach is presented. At each simulation step and for each node of the ITN the proposed approach assigns container flows to each of the outgoing links in a receding horizon way. To be specific, for a simulation period of $N_{\text{sim}}T_{\text{s}}$ h, a dynamic transport demand (o,d) (the volume of this transport demand is denoted by $d_{o,d}(k)$) needs to be served over an ITN with an initial network state given by $\tilde{\mathbf{x}}_1(0)$ and $\tilde{\mathbf{x}}_2(0)$. So, at the simulation step k, flow assignments $\left[y_{i,j,o,d}^{m}(k),\ldots,y_{i,j,o,d}^{m}(k+N_{\text{pred}}-1)\right]^{\text{T}}$ for each outgoing link of each node over the prediction horizon $\left[kT_{\text{s}},(k+N_{\text{pred}})T_{\text{s}}\right]$ are determined by solving a nonlinear optimization problem (19). At the simulation step k the initial network states of the ITN is $\tilde{\mathbf{x}}_1(k)$ and $\tilde{\mathbf{x}}_2(k)$. The optimization problem at simulation step k takes into account not only the current and estimated transport demand and traffic condition information but also the predicted network behavior of the dynamic ITN in the prediction horizon $\left[kT_{\text{s}},(k+N_{\text{pred}})T_{\text{s}}\right]$. Only the intermodal container flow assignment $y_{i,j,o,d}^{m}(k)$ at simulation step k is actually implemented. For the next simulation step $k+1$ the initial network state is updated and dynamic transport demand and traffic condition information for the next prediction horizon $\left[(k+1)T_{\text{s}},(k+N_{\text{pred}}+1)T_{\text{sim}}\right]$ are collected and estimated. At the next simulation step $k+1$, the same optimization and updating procedure is conducted again. This procedure continues iteratively until the end of the entire simulation period $N_{\text{sim}}T_{\text{s}}$ h. The proposed receding horizon intermodal container flow assignment approach is illustrated as follows:

Initialization : An ITN, $\tilde{\mathbf{x}}_1(0)$, $\tilde{\mathbf{x}}_2(0)$, $\tilde{\mathbf{d}}_{o,d}(0) = \left[d_{o,d}(0),\ldots,d_{o,d}(N_{\text{pred}}-1)\right]^{\text{T}}$ for all $(o,d) \in \mathscr{O}_{\text{od}}$, N_{sim}, N_{pred}, $\tilde{\rho}_{i,j}^{\text{truck}}(0) = \left[\rho_{i,j}^{\text{truck}}(0),\ldots,\rho_{i,j}^{\text{truck}}(N_{\text{pred}}-1)\right]^{\text{T}}$ on all freeways.
$k \leftarrow 0$
while $k < N_{\text{sim}}$ **do**
  $\tilde{\mathbf{x}}_1(k), \tilde{\mathbf{x}}_2(k), \tilde{\mathbf{y}}(k) \leftarrow$ solution of the optimization problem (19) for simulation step k
  Implement the intermodal container flow assignment $y_{i,j,o,d}^{m}(k)$ at each node's outgoing links at simulation step k
  $\tilde{\mathbf{x}}_1(k+1)$, $\tilde{\mathbf{x}}_2(k+1) \leftarrow$ initial network state for simulation step $k+1$
  $\tilde{\mathbf{d}}_{o,d}(k+1), \tilde{\rho}_{i,j}^{\text{truck}}(k+1) \leftarrow$ dynamic transport demand and dynamic traffic condition information for the next prediction horizon $\left[(k+1)T_{\text{s}},(k+N_{\text{pred}}+1)T_{\text{sim}}\right]$
  $k \leftarrow k+1$
end while
$J_{\text{optimal}} \leftarrow$ value of the objective function corresponding to the intermodal container flow assignments made during the entire simulation period of $N_{\text{sim}}T_{\text{s}}$ hours
End

4 SIMULATION STUDY

In this section, the proposed receding horizon intermodal container flow assignment approach is implemented for a small-size ITN.

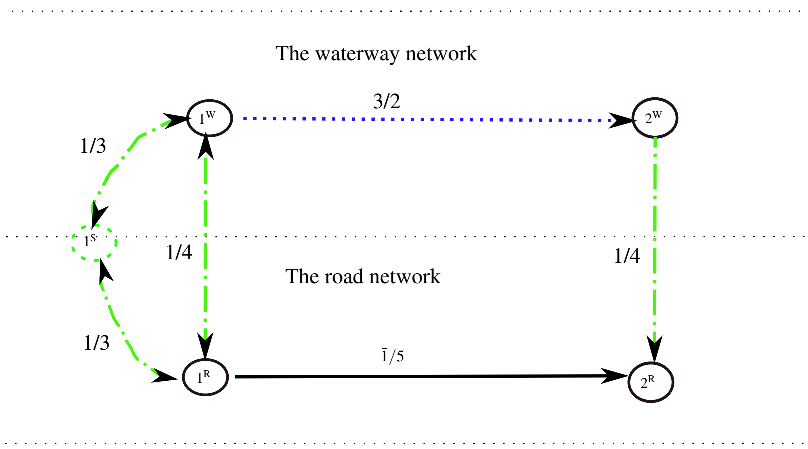

FIGURE 2 An ITN with 5 nodes and 2 modes.

TABLE 1 The typical transport time $r_{i,d}$ (h) and the typical transport cost $c_{i,d}$ (€/TEU)

$r_{i,d}/c_{i,d}$	1^{S}	1^{W}	1^{R}	2^{W}	2^{R}
1^{S}	0/0	2/3	2/3	7/11	9/16
1^{W}	2/3	0/0	1/3	4/6	7/14
1^{R}	2/3	1/3	0/0	6/14	4/12
2^{W}	–/–	–/–	–/–	0/0	2/3
2^{R}	–/–	–/–	–/–	–/–	0/0

4.1 The intermodal container assignment problem

We consider an ITN of Figure 2. The network comprises of 5 nodes (i.e., 2 truck terminals, 2 barge terminals, and 1 storage yard.), 1 link with the barge connection, 1 link with the truck connection, and another 7 modality transfer links. The transport/transfer times and transport costs on links are shown as labels of each link in Figure 2. For example, the label "$1/4$" for the transfer link from node 1^{W} to node 1^{R} indicates that it takes 1 h to transfer from the barge terminal to the road terminal and the modality transfer cost is 4 €/TEU/h. Note that for the freeway link $l^{\mathrm{truck}}_{1^{\mathrm{R}},2^{\mathrm{R}}}$ the link transport time is load-dependent, and therefore the corresponding label only shows the typical transport time on this freeway link. The typical transport times and the typical delivery costs between any pair of nodes of the network are given in Table 1. The capacities on nodes and links are taken to be unlimited.

The intermodal container flow assignment process is simulated for a period of 8 h and the simulation time step, T_{s}, is chosen as 1 h. Barges are scheduled to departure from node 1^{W} with a frequency of once per hour. On the freeway link $l^{\mathrm{truck}}_{1^{\mathrm{R}},2^{\mathrm{R}}}$, trucks are always available for delivering containers, and the traffic density induced by other traffic flows is given in Table 2. The typical length of trucks is assumed to be twice that of cars. There is a piecewise constant transport demand entering a deep-sea terminal at node 1^{W} and going to node 2^{R} during the simulation period, as given in Table 2. The conversion factor α in (14) is taken as 5. This implies that the transport time has a large influence compared with the transport cost on the optimal container flow assignment. For the above intermodal freight transport setup, the initial state of the network is taken to be empty (e.g., $x_{i,o,d}(k) = 0$ and $x^{m}_{i,j,o,d}(k) = 0$ for $\forall (o,d) \in \mathscr{O}_{\mathrm{od}}, \forall\ (i,j,m) \in \mathscr{E}, \forall\ k \leq 0$).

TABLE 2 Densities of other traffic flows on road links and transport demand

Period (h)	0 – 1	1 – 5	5 – 6	6 – 14
$\rho_{1^{R},2^{R}}^{\text{truck,oth}}$ (veh/km/lane)	18.0	42.0	18.0	18.0
$d_{1^{W},2^{R}}$ (TEU/h)	130	270	130	0

4.2 The all-or-nothing approach

For the user-supplied objective function (14) and the density condition of other traffic flows on the freeway link $l_{1^{R},2^{R}}^{\text{truck}}$ given in Table 2, the all-or-nothing approach selects an optimal routing from node 1^{W} to node 2^{R} with a delivery cost of 19 €/TEU for a transport time of 1 h on link $l_{1^{R},2^{R}}^{\text{truck}}$ or 29 €/TEU for a transport time of 2 h on link $l_{1^{R},2^{R}}^{\text{truck}}$. The selected optimal routing is to first change from the waterway network to the freeway network through the transfer link from node 1^{W} to node 1^{R}, and next to go to the destination by trucks on link $l_{1^{R},2^{R}}^{\text{truck}}$. The evolution of the number of containers on nodes and links of the ITN is illustrated with solid red lines in Figure 3 and Figure 4, respectively. When container flows arrive node 1^{R}, they can immediately enter link $l_{1^{R},2^{R}}^{\text{truck}}$ due to the assumption of unlimited capacities of nodes and links. Therefore, the number of containers in all nodes and on all unselected links of the ITN are zero in Figure 3 and Figure 4. However, the assigned container flows increase the traffic density on freeway link $l_{1^{R},2^{R}}^{\text{truck}}$, thus leading to a longer link transport time i.e., 3 h on link $l_{1^{R},2^{R}}^{\text{truck}}$ from simulation step 2 to simulation step 5 (see Figure 5). For the case of a link transport time of 3 h on $l_{1^{R},2^{R}}^{\text{truck}}$, the previously selected optimal route does no longer correspond to the minimum-cost path between node 1^{W} and node 2^{R}. In this situation, the delivery cost will increase, thus leading to a worse performance. The all-or-nothing approach cannot address this situation.

4.3 The receding horizon approach

The proposed receding horizon intermodal container flow assignment approach is implemented with a prediction horizon of 6 h. The optimal intermodal container flow assignments are determined subject to the user-supplied objective function (14). The evolution of the number of containers on nodes and links of the ITN is shown with dashed blue lines in Figure 3 and Figure 4, respectively.

In the receding horizon approach, two routes are mainly selected for the intermodal container transport process: '$1^{W} - 1^{R} - 2^{R}$' and '$1^{W} - 2^{W} - 2^{R}$'. The route '$1^{W} - 2^{W} - 2^{R}$' is selected to prevent a longer than 2 h transport time on freeway link $l_{1^{R},2^{R}}^{\text{truck}}$. The effect can be seen in Figure 5. The presence of containers on other nodes and links except for these two routes in the ITN is due to the fact that the global optimal solution of the nonlinear optimization problem (19) cannot be guaranteed in each simulation step.

The values of the objective function defined in (14) are respectively 64540 € and 47975 € for the all-or-nothing approach and the receding horizon approach. This implies a 25.67% reduction of the total delivery cost for the proposed receding horizon approach compared with the all-or-nothing approach.

5 CONCLUSIONS AND FUTURE RESEARCH

The intermodal container flow assignment problem in hinterland haulage between deep-sea terminals and inland terminals has been investigated in this paper. The load-dependent transport times on freeways of the ITN have been considered. We have proposed a so-called receding horizon intermodal container flow assignment approach based on a dynamic ITN model. In the proposed approach container flow assignments are determined at each time step at each node of the network in a receding horizon fashion. At each time step the proposed approach assigns container flows by solving a nonlinear optimization problem while taking the

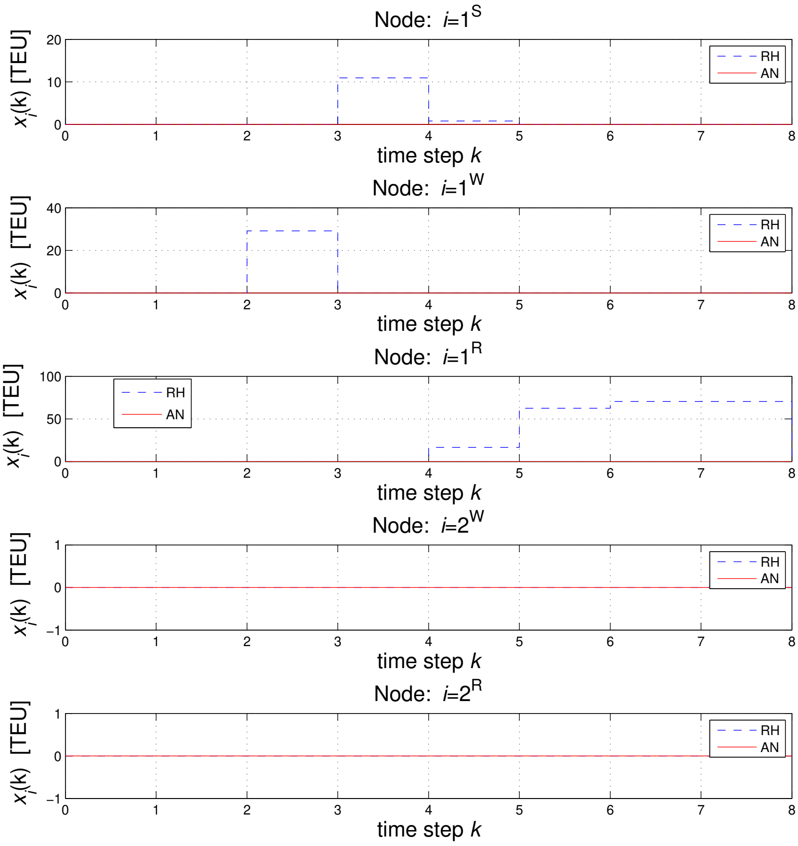

FIGURE 3 The evolution of the number of containers in nodes of the ITN. 'RH' and 'AN' in the legend denote the receding horizon approach and the all-or-nothing approach, respectively.

future transport demands and traffic conditions and the evolution of the network for a certain prediction period into account. The potential of this approach has been compared with the all-or-nothing approach on a small-size ITN and it was concluded that the newly proposed approach performs significantly better.

For the future work, the effect of economics of scale on the railway and waterway transport in intermodal container flow assignment will be investigated. We will also conduct case studies for large-scale ITNs with more modes of transport and capacity constraints on nodes and links.

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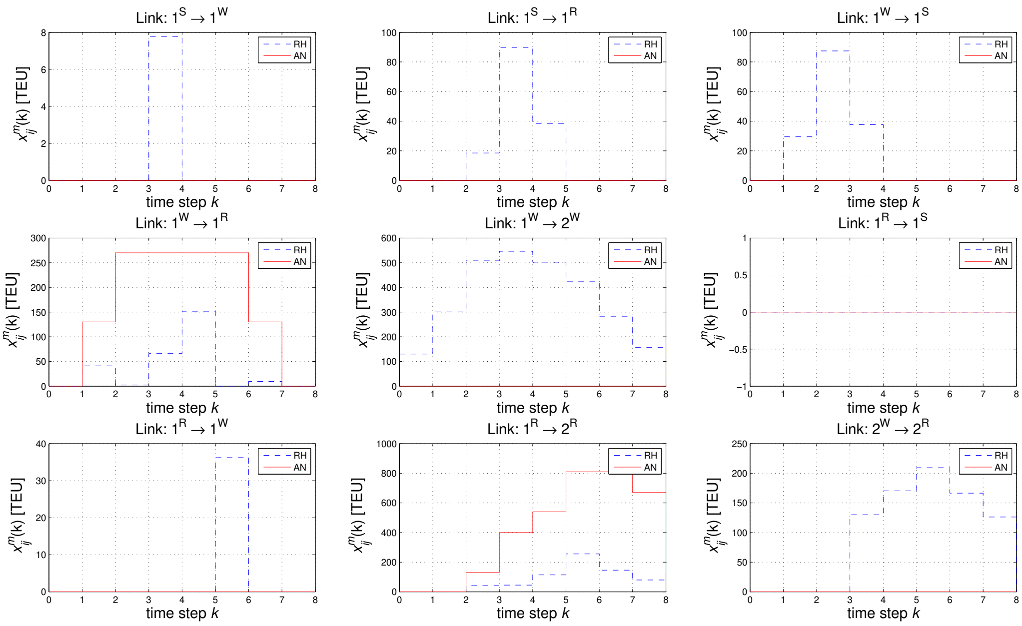

FIGURE 4 The evolution of the number of containers on links of the ITN. 'RH' and 'AN' in the legend denote the receding horizon approach and the all-or-nothing approach, respectively.

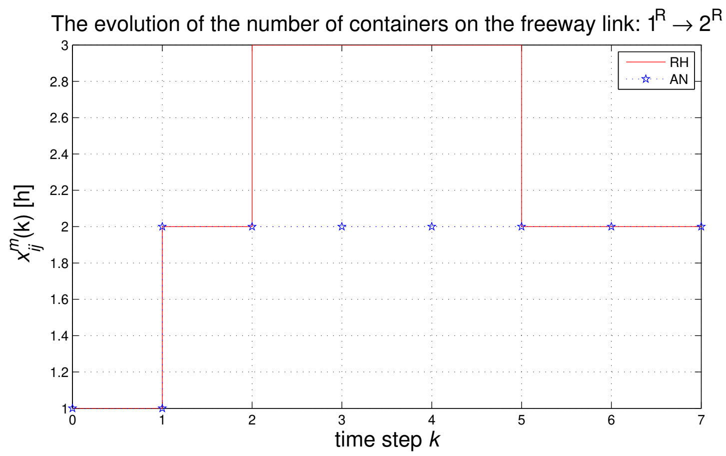

FIGURE 5 The evolution of the link transport time on link $l^{\text{truck}}_{1^{\text{R}},2^{\text{R}}}$. 'RH' and 'AN' in the legend denote the receding horizon approach and the all-or-nothing approach, respectively.

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