

Technical report 14-008

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L. Li, R.R. Negenborn, and B. De Schutter

If you want to cite this report, please use the following reference instead:

L. Li, R.R. Negenborn, and B. De Schutter, "A receding horizon approach for container flow assignment in intermodal freight transport," *Proceedings of the 93rd Annual Meeting of the Transportation Research Board*, Washington, DC, 14 pp., Jan. 2014. Paper 14-0088.

Delft Center for Systems and Control
Delft University of Technology
Mekelweg 2, 2628 CD Delft
The Netherlands
phone: +31-15-278.24.73 (secretary)
URL: <https://www.dcsc.tudelft.nl>

*This report can also be downloaded via https://pub.deschutter.info/abs/14_008.html

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

Submission date: 13/11/2013

Word count: 5749 words + (5 figures + 2 tables)*(250 words) = 7499 words

Authors:

L. Li¹, Delft Center for Systems and Control, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands, phone: +31-15-278 52 42, email: l.li-1@tudelft.nl

R. R. Negenborn, Department of Marine and Transport Technology, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands, phone: +31-15-278 67 18, email: r.r.negenborn@tudelft.nl

B. De Schutter, Delft Center for Systems and Control, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands, phone: +31-15-278 51 13, email: b.deschutter@tudelft.nl

¹Corresponding author

1 ABSTRACT

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

1 INTRODUCTION

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

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

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

36 Intermodal container assignment determines how much volume of the transport demand will be
37 assigned to each of the candidate routes in order to deliver a transport demand from its origin node to its
38 destination node over an ITN. These candidate routes are the outcome of intermodal routing methods (8).
39 When considering unlimited capacities of transport connections, in practice typically an all-or-nothing ap-
40 proach is adopted to assign the transport demand. That is, the entire volume of the transport demand will
41 be assigned to the route that leads to the minimum value of the user-supplied objective function given by
42 intermodal freight forwarders. In practice, the transport demand and the traffic conditions in the network
43 show dynamic behavior, e.g., unexpected transport order requests, transport order cancellations, the evolu-
44 tion of the transport times on freeway links, etc. These dynamic behaviors cannot be estimated with a high
45 precision for a long time period. In this paper, we study intermodal freight transport problems from a system
46 and control perspective by considering dynamic ITN models and determining intermodal routing and inter-
47 modal container assignment by solving an optimization problem. We propose a so-called receding horizon

1 intermodal container flow assignment approach that uses a dynamic ITN model based on the authors' earlier
 2 work (16). The intermodal container flow assignments are updated in a receding horizon way to address
 3 the dynamic changes of the transport demand and the traffic conditions. The dynamic ITN model allows
 4 the prediction of the network behavior based on information on the current and estimated future transport
 5 demands and traffic conditions. The predicted network behavior information benefits the decision-making
 6 of freight forwarders and enables container flows being assigned in a way such that unexpected transport
 7 situations (e.g., road congestion, overlong delays, etc.) are partially or even completely avoided.

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

13 2 INTERMODAL TRANSPORT NETWORK MODEL

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

18 2.1 Dynamics of the ITN

19 An ITN can be represented as a directed graph $\mathcal{G}(\mathcal{V}, \mathcal{E}, \mathcal{M})$. The node set $\mathcal{V} = \mathcal{V}_{\text{truck}} \cup \mathcal{V}_{\text{train}} \cup \mathcal{V}_{\text{barge}} \cup \mathcal{V}_{\text{store}}$
 20 is a finite nonempty set, in which the storage node set $\mathcal{V}_{\text{store}}$ represents storage yards shared by different
 21 single-mode terminals inside each intermodal terminal of the network. The sets $\mathcal{V}_{\text{truck}}$, $\mathcal{V}_{\text{train}}$, and $\mathcal{V}_{\text{barge}}$
 22 represent truck terminals, train terminals, and barge terminals inside each intermodal terminal of the net-
 23 work, respectively. The set $\mathcal{M} = \mathcal{M}_1 \cup \mathcal{M}_2$ represents transport modes and mode transfer types in the net-
 24 work with $\mathcal{M}_1 = \{\text{truck, train, barge, store}\}$ and $\mathcal{M}_2 = \{m_1 \rightarrow m_2 | m_1, m_2 \in \mathcal{M}_1 \text{ and } m_1 \neq m_2\}$. The link set
 25 $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V} \times \mathcal{M}$ represents all available connections among nodes. A link (i, j, m) with $i, j \in \mathcal{V}$ and $m \in \mathcal{M}$
 26 will be denoted by $l_{i,j}^m$. Depending on whether a mode transfer happens or not in one link, this link is cat-
 27 egorized as transfer link or transport link, respectively. Figure 1 presents an ITN model to illustrate the
 28 elements mentioned above.

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

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

32

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

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

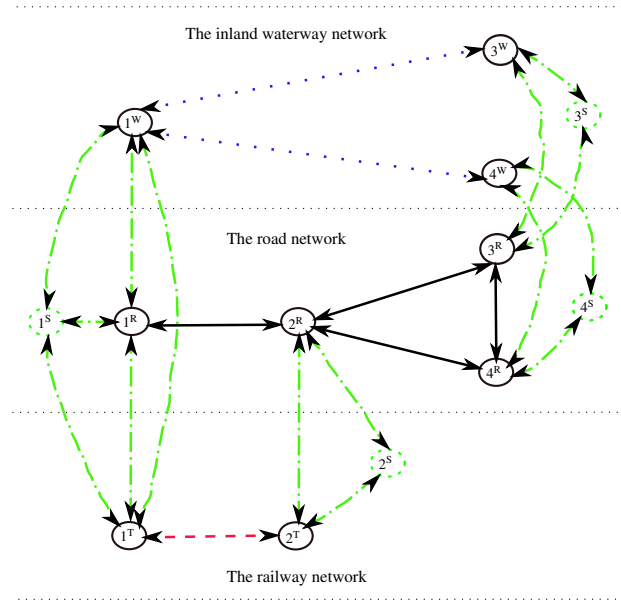


FIGURE 1 An ITN model. The nodes 1^R , 1^T , 1^W , and 1^S represent the truck terminal, the train terminal, the barge terminal and the storage yard at intermodal terminal 1, respectively. The dotted blue arcs, the solid black arcs, the dashed red arcs, and the dash-dotted green arcs indicate 4 transport 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.

1

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

2

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

$$i_{i,j}^{\text{truck}}(k) = \mathbf{round} \left(\frac{L_{i,j}^{\text{truck}}}{v_{i,j}^{\text{truck,truck}}(k) T_s} \right), \quad (6)$$

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

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

3

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

$$\sum_{(o,d) \in \mathcal{O}_{\text{od}}} x_{i,o,d}(k) \leq S_i, \forall i \in \mathcal{V}, \forall k, \quad (10)$$

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

1

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

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

2 where

3 - $x_{i,o,d}(k)$ (TEU) is the number of containers corresponding to transport demand (o,d) and staying at
4 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 $l_{j,i}^m$, $(j,m) \in \mathcal{N}_i^{\text{in}}$ at time step k where the set $\mathcal{N}_i^{\text{in}}$ is defined as

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

5 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
6 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 $l_{i,j}^m$, $(j,m) \in \mathcal{N}_i^{\text{out}}$ at time step k where the set $\mathcal{N}_i^{\text{out}}$ is defined as

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

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

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

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

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

$$\begin{aligned} T_{i,j}^m(k) &= t_{i,j}^m(k)T_s, \\ t_{i,j}^m(k) &\in \mathbb{N} \setminus \{0\}, \\ t_{i,j}^m(k) &\leq t_{i,j}^{m,\text{max}}, \end{aligned}$$

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

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

20 - $q_{i,j,o,d}^{m,\text{in}}(k)$ (TEU/h) is the container flow corresponding to transport demand (o,d) and entering link
21 $l_{i,j}^m$ at time step k .

- 1 - $x_{i,j,o,d}^m(k)$ (TEU) is the number of containers corresponding to transport demand (o,d) and traveling
 2 in link $l_{i,j}^m$ at time step k .
- 3 - $\rho_{i,j}^{\text{truck,truck}}(k)$ is the actual traffic density corresponding to freight truck flow on link $l_{i,j}^{\text{truck}}$ at time step
 4 k .
- 5 - $\rho_{i,j}^{\text{truck,oth}}(k)$ is the traffic density induced by the other traffic on link $l_{i,j}^{\text{truck}}$ at time step k .
- 6 - L_{truck} (m) and L_{oth} (m) are the typical length of freight trucks and other vehicles, respectively.
- 7 - $L_{i,j}^{\text{truck}}$ (km) and $\lambda_{i,j}^{\text{truck}}$ are the length and the number of lanes of link $l_{i,j}^{\text{truck}}$, respectively.
- 8 - $v_{i,j}^{\text{truck,truck}}(k)$ and $t_{i,j}^{\text{truck}}(k)$ are the average speed and the average transport time of container flow on
 9 freeway link $l_{i,j}^{\text{truck}}$ at time step k , respectively.
- 10 - $v_{i,j,\text{free}}^{\text{truck,truck}}$, $a_{i,j}^{\text{truck,truck}}$ and $\rho_{i,j,\text{crit}}^{\text{truck,truck}}$ are the model parameters in the fundamental diagram model. These
 11 three model parameters have typical values as: $v_{i,j,\text{free}}^{\text{truck,truck}} = 120$ km/h, $\rho_{i,j,\text{crit}}^{\text{truck,truck}} = 33.5$ veh/km/lane,
 12 and $a_{i,j}^{\text{truck,truck}} = 1.867$ (17, 18).
- 13 - h_i^{in} (TEU/h) and h_i^{out} (TEU/h) are the maximal container unloading and loading rates of the equip-
 14 ment in node i , respectively.
- 15 - S_i (TEU) is the storage capacity in node i .
- 16 - $C_{i,j}^m$ (TEU) is the transport or transfer capacity of link $l_{i,j}^m$.
- 17 - $C_{i,j}^{m,\text{in}}$ (TEU/h) is the maximal volume of container flows that can enter link $l_{i,j}^m$ at each time step.

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

27 2.2 The optimal container flow assignment problem

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

$$J = \alpha(J_1 + J_2) + J_3 + J_4 \quad (14)$$

31 with

$$J_1 = \sum_{(o,d) \in \mathcal{O}_{\text{od}}} w_{o,d} \left[\sum_{k=1}^{N-1} \left[\sum_{i \in \mathcal{V}} x_{i,o,d}(k) T_s + \sum_{(i,j,m) \in \mathcal{E}} x_{i,j,o,d}^m(k) T_s \right] \right] \quad (15)$$

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

$$J_3 = \sum_{(o,d) \in \mathcal{O}_{od}} w_{o,d} \left[\sum_{k=1}^{N-1} \left[\sum_{i \in \mathcal{V}} x_{i,o,d}(k) T_s C_{i,\text{store}}(k) + \sum_{(i,j,m) \in \mathcal{E}} x_{i,j,o,d}^m(k) T_s C_{i,j,\text{tran}}^m(k) \right] \right] \quad (17)$$

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

1 where

- 2 - J_1, J_3 are the total transport time and the total delivery cost of transport demands \mathcal{O}_{od} and J_2, J_4 are
- 3 penalties on the unfinished transport demands at the end of the planning horizon.
- 4 - $w_{o,d} \in (0, 1]$ indicates the relative priority of the transport demand (o, d) ; the relation $\sum_{(o,d) \in \mathcal{O}_{od}} w_{o,d} =$
- 5 1 always holds.
- 6 - $C_{i,\text{store}}(k)$ (€/TEU/h) is the cost associated with storing containers in the node i at time step k .
- 7 - $C_{i,j,\text{tran}}^m(k)$ (€/TEU/h) is the transport or transfer cost, i.e., the cost that has to be paid for the use of a
- 8 link to transport or transfer containers at time step k .
- 9 - $r_{i,d}$ (h/TEU) and $c_{i,d}$ (€/TEU) are the typical² transport time and the typical delivery cost for contain-
- 10 ers being transported from node i to destination node d , respectively.
- 11 - $r_{i,j}^{m,d}$ (h/TEU) and $c_{i,j}^{m,d}$ (€/TEU) are the typical³ transport time and the typical delivery cost for con-
- 12 tainers being transported from link $l_{i,j}^m$ to destination node d , respectively.
- 13 - α (€/h) is the conversion factor for converting transport times to the equivalent monetary cost.
- 14 - $N \cdot T_s$ (h) is the planning horizon with $N \in \mathbb{N} \setminus \{0\}$. In the receding horizon intermodal container flow
- 15 assignment approach in Section 3, N_{sim} is the step length of the whole simulation; N_{pred} is the step
- 16 length of the prediction horizon at each simulation step, respectively.

Therefore, the optimal container flow assignment problem can be formulated as the following non-linear optimization problem:

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

17

subject to (1) – (13).

18 where

- 19 - $\tilde{\mathbf{x}}_1$ contains all $x_{i,o,d}(k)$, for $i \in \mathcal{V}, (o, d) \in \mathcal{O}_{od}, k = 1, \dots, N$,
- 20 - $\tilde{\mathbf{x}}_2$ contains all $x_{i,j,o,d}^m(k)$, for $(i, j, m) \in \mathcal{E}, (o, d) \in \mathcal{O}_{od}, k = 1, \dots, N$,
- 21 - $\tilde{\mathbf{y}}$ contains all $y_{i,j,o,d}^m(k)$, for $i \in \mathcal{V}, (j, m) \in \mathcal{N}_i^{\text{out}}, (o, d) \in \mathcal{O}_{od}, k = 1, \dots, N$,
- 22 - $\tilde{\mathbf{u}}$ contains all $u_{j,i,o,d}^m(k)$, for $i \in \mathcal{V}, (j, m) \in \mathcal{N}_i^{\text{in}}, (o, d) \in \mathcal{O}_{od}, k = 1, \dots, N$,

²The values of $r_{i,d}$ and $c_{i,d}$ can be obtained from statistical data.

³The values of $r_{i,j}^{m,d}$ and $c_{i,j}^{m,d}$ can be obtained from statistical data.

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

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

6 3 A RECEDING HORIZON CONTAINER FLOW ASSIGNMENT APPROACH

7 In this section, a so-called receding horizon intermodal container flow assignment approach is presented.
8 At each simulation step and for each node of the ITN the proposed approach assigns container flows to
9 each of the outgoing links in a receding horizon way. To be specific, for a simulation period of $N_{\text{sim}}T_s$ h,
10 a dynamic transport demand (o, d) (the volume of this transport demand is denoted by $d_{o,d}(k)$) needs to be
11 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 ,
12 flow assignments $\left[y_{i,j,o,d}^m(k), \dots, y_{i,j,o,d}^m(k + N_{\text{pred}} - 1) \right]^T$ for each outgoing link of each node over the pre-
13 diction horizon $[kT_s, (k + N_{\text{pred}})T_s]$ are determined by solving a nonlinear optimization problem (19). At
14 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
15 simulation step k takes into account not only the current and estimated transport demand and traffic con-
16 dition information but also the predicted network behavior of the dynamic ITN in the prediction horizon
17 $[kT_s, (k + N_{\text{pred}})T_s]$. Only the intermodal container flow assignment $y_{i,j,o,d}^m(k)$ at simulation step k is actually
18 implemented. For the next simulation step $k + 1$ the initial network state is updated and dynamic transport
19 demand and traffic condition information for the next prediction horizon $[(k + 1)T_s, (k + N_{\text{pred}} + 1)T_{\text{sim}}]$ are
20 collected and estimated. At the next simulation step $k + 1$, the same optimization and updating proce-
21 dure is conducted again. This procedure continues iteratively until the end of the entire simulation period
22 $N_{\text{sim}}T_s$ h. The proposed receding horizon intermodal container flow assignment approach is illustrated as
23 follows:

24 **Initialization** : An ITN, $\tilde{\mathbf{x}}_1(0), \tilde{\mathbf{x}}_2(0), \tilde{\mathbf{d}}_{o,d}(0) = [d_{o,d}(0), \dots, d_{o,d}(N_{\text{pred}} - 1)]^T$ for all $(o, d) \in \mathcal{O}_{\text{od}}, N_{\text{sim}},$
25 $N_{\text{pred}}, \tilde{\rho}_{i,j}^{\text{truck}}(0) = [\rho_{i,j}^{\text{truck}}(0), \dots, \rho_{i,j}^{\text{truck}}(N_{\text{pred}} - 1)]^T$ on all freeways.
26 $k \leftarrow 0$
27 **while** $k < N_{\text{sim}}$ **do**
28 $\tilde{\mathbf{x}}_1(k), \tilde{\mathbf{x}}_2(k), \tilde{\mathbf{y}}(k) \leftarrow$ solution of the optimization problem (19) for simulation step k
29 Implement the intermodal container flow assignment $y_{i,j,o,d}^m(k)$ at each node's outgoing links at simu-
30 lation step k
31 $\tilde{\mathbf{x}}_1(k + 1), \tilde{\mathbf{x}}_2(k + 1) \leftarrow$ initial network state for simulation step $k + 1$
32 $\tilde{\mathbf{d}}_{o,d}(k + 1), \tilde{\rho}_{i,j}^{\text{truck}}(k + 1) \leftarrow$ dynamic transport demand and dynamic traffic condition information for
33 the next prediction horizon $[(k + 1)T_s, (k + N_{\text{pred}} + 1)T_{\text{sim}}]$
34 $k \leftarrow k + 1$
35 **end while**
36 $J_{\text{optimal}} \leftarrow$ value of the objective function corresponding to the intermodal container flow assignments
37 made during the entire simulation period of $N_{\text{sim}}T_s$ hours
38 **End**

39 4 SIMULATION STUDY

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

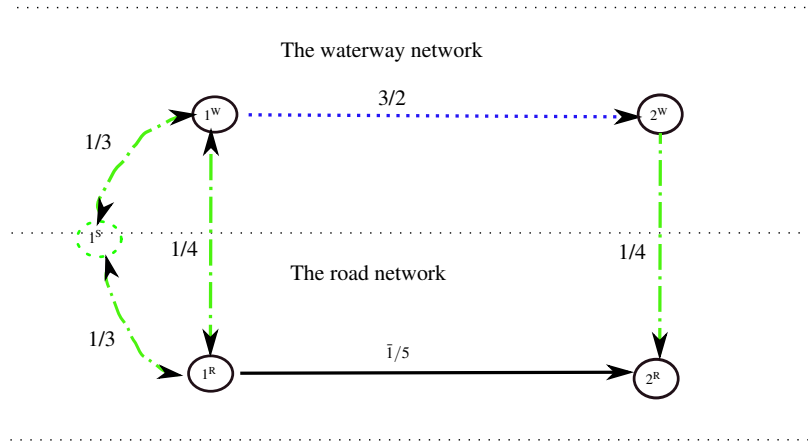


FIGURE 2 An ITN with 5 nodes and 2 modes.

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 $l_{1^R,2^R}^{\text{truck}}$ 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 $l_{1^R,2^R}^{\text{truck}}$, 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 $x_{i,j,o,d}^m(k) = 0$ for $\forall(o,d) \in \mathcal{O}_{od}, \forall(i,j,m) \in \mathcal{E}, \forall k \leq 0$).

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

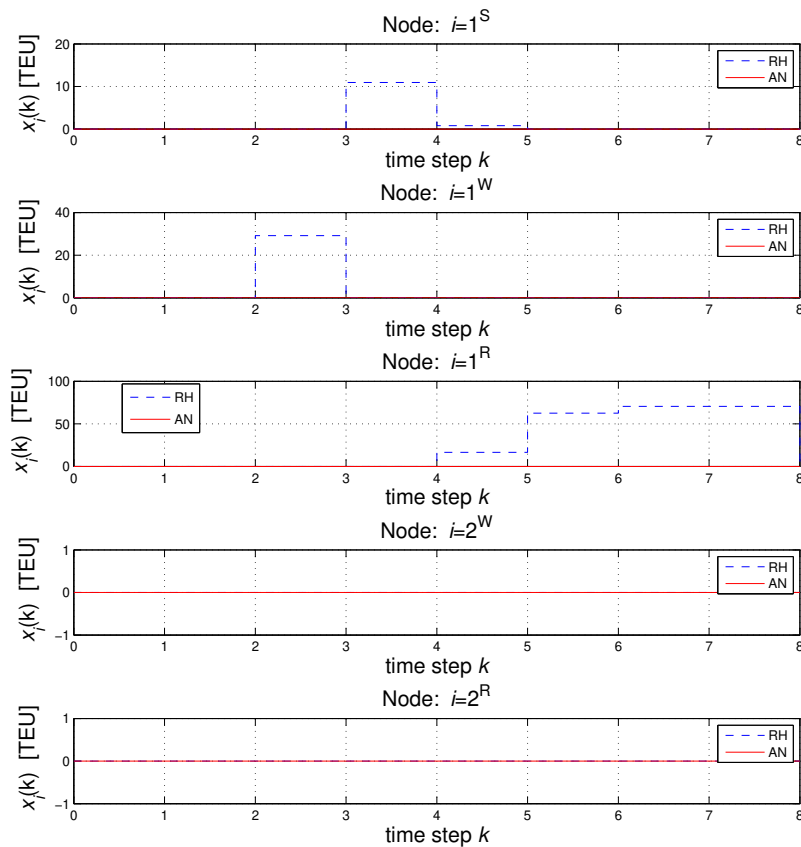


FIGURE 3 The evolution of the number of containers in nodes of the ITN. ‘RH’ and ‘AN’ in the legend denote the receding horizon approach and the all-or-nothing approach, respectively.

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

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

7 ACKNOWLEDGMENTS

8 This research is supported by the China Scholarship Council under Grant 2011629027 and the VENI project
 9 “Intelligent multi-agent control for flexible coordination of transport hubs” (project 11210) of the Dutch
 10 Technology Foundation STW.

11 REFERENCES

12 [1] Port of Rotterdam Authority, Port Vision 2030: Port Compass, Dec. 2011, URL

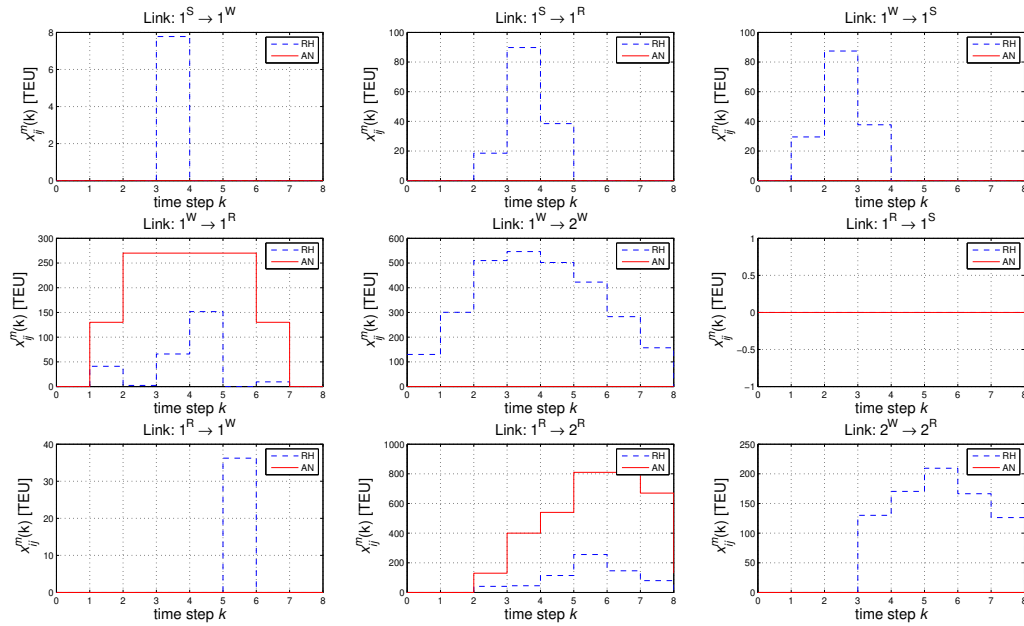


FIGURE 4 The evolution of the number of containers on links of the ITN. ‘RH’ and ‘AN’ in the legend denote the receding horizon approach and the all-or-nothing approach, respectively.

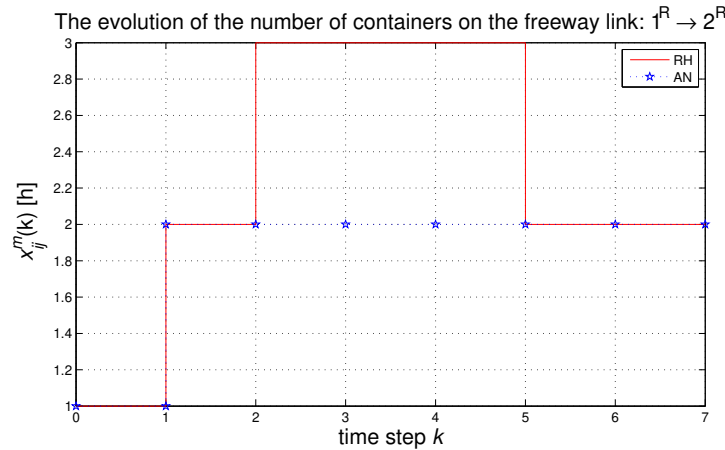


FIGURE 5 The evolution of the link transport time on link $l_{1^R, 2^R}^{truck}$. ‘RH’ and ‘AN’ in the legend denote the receding horizon approach and the all-or-nothing approach, respectively.

1 [http://www.portofrotterdam.com/en/Port/port-in-general/port-vision-2030/Documents/Port-Vision-](http://www.portofrotterdam.com/en/Port/port-in-general/port-vision-2030/Documents/Port-Vision-2030.pdf)
 2 [2030.pdf](http://www.portofrotterdam.com/en/Port/port-in-general/port-vision-2030/Documents/Port-Vision-2030.pdf).
 3 [2] Europe Container Terminal, *The future of freight transport*. Europe Container Terminal, Rotterdam,
 4 The Netherlands, Oct. 2011.
 5 [3] Crainic, T. G., and K. H. Kim, Intermodal transportation. In *Transportation* (C. Barnhart, and G. La-
 6 porte, editors), vol. 14 of *Handbooks in Operations Research and Management Science*, chap. 8, Else-
 7 vier, 2007, pp. 467–537.

- 1 [4] United Nations Economic Commission for Europe (UNECE), Glossary for Transport Statistics, Fourth
2 ed., Jul. 2009, URL www.unece.org/fileadmin/DAM/trans/main/wp6/pdfdocs/glossen4.pdf.
- 3 [5] Macharis, C., and Y. M. Bontekoning, Opportunities for OR in intermodal freight transport research:
4 a review. *European Journal of Operational Research*, vol. 153, no. 2, 2004, pp. 400–416.
- 5 [6] Jarzemskiene, I., The evolution of intermodal transport research and its development issues. *Transport*,
6 vol. 22, no. 4, 2007, pp. 296–306.
- 7 [7] Caris, A., C. Macharis, and G. Janssens, Planning problems in intermodal freight transport: accomplish-
8 ments and prospects. *Transportation Planning and Technology*, vol. 31, no. 3, 2008, pp. 277–302.
- 9 [8] Caris, A., C. Macharis, and G. Janssens, Decision support in intermodal transport: A new research
10 agenda. *Computers in Industry*, vol. 64, no. 2, 2013, pp. 105–112.
- 11 [9] Barnhart, C., and H. Ratliff, Modeling intermodal routing. *Journal of Business Logistics*, vol. 14, no. 1,
12 1993, pp. 205–223.
- 13 [10] Boardman, B., E. Malstrom, D. Butler, and M. Cole, Computer assisted routing of intermodal ship-
14 ments. *Computers and Industrial Engineering*, vol. 33, no. 1-2, 1997, pp. 311–314.
- 15 [11] Ziliaskopoulos, A., and W. Wardell, An intermodal optimum path algorithm for multimodal networks
16 with dynamic arc travel times and switching delays. *European Journal of Operational Research*, vol.
17 125, no. 3, 2000, pp. 486–502.
- 18 [12] Chang, T.-S., Best routes selection in international intermodal networks. *Computers and Operations*
19 *Research*, vol. 35, no. 9, 2008, pp. 2877–2891.
- 20 [13] Ayed, H., Z. Habas, D. Khadraoui, and C. Galvez-Fernandez, A parallel algorithm for solving time
21 dependent multimodal transport problem. In *Proceedings of the 14th International IEEE Conference*
22 *on Intelligent Transportation Systems (ITSC 2011)*, Washington, DC, USA, Oct. 2011, pp. 722–727.
- 23 [14] Grasman, S. E., Dynamic approach to strategic and operational multimodal routing decisions. *Interna-*
24 *tional Journal of Logistics Systems and Management*, vol. 2, no. 1, 2006, pp. 96–106.
- 25 [15] Cho, J., H. Kim, and H. Choi, An intermodal transport network planning algorithm using dynamic
26 programming-A case study: From Busan to Rotterdam in intermodal freight routing. *Applied Intelli-*
27 *gence*, vol. 36, no. 3, 2012, pp. 529–541.
- 28 [16] Li, L., R. R. Negenborn, and B. De Schutter, A sequential linear programming approach for flow
29 assignment in intermodal freight transport. In *Proceedings of the 16th IEEE International Conference*
30 *on Intelligent Transport Systems (ITSC 2013)*, The Hague, The Netherlands, Oct. 2013, pp. 1124–1230.
- 31 [17] Kotsialos, A., M. Papageorgiou, and A. Messmer, Optimal coordinated and integrated motorway net-
32 work traffic control. In *Proceedings of 14th International Symposium on transportation and Traffic*
33 *Theory*, Jerusalem, Israel, Jul. 1999, pp. 621–644.
- 34 [18] Hegyi, A., B. De Schutter, and H. Hellendoorn, Model predictive control for optimal coordination of
35 ramp metering and variable speed limits. *Transportation Research Part C: Emerging Technologies*,
36 vol. 13, no. 3, 2005, pp. 185 – 209.