Delft University of Technology

Delft Center for Systems and Control

Technical report 14-038

Multi-agent cooperative transport planning of intermodal freight transport*

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, "Multi-agent cooperative transport planning of intermodal freight transport," *Proceedings of the 17th International IEEE Conference on Intelligent Transportation Systems (ITSC 2014)*, Qingdao, China, pp. 2465–2471, Oct. 2014.

Delft Center for Systems and Control
Delft University of Technology
Mekelweg 2, 2628 CD Delft
The Netherlands
phone: +31-15-278.51.19 (secretary)
fax: +31-15-278.66.79
URL: http://www.dcsc.tudelft.nl

Multi-Agent Cooperative Transport Planning of Intermodal Freight Transport

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

Abstract— **This paper proposes a multi-agent cooperative intermodal freight transport planning approach for multiple intermodal freight transport operators (IFTOs) in the control of container flows. The cooperation goal is to minimize the overall freight delivery cost for serving certain transport demands. Based on a distributed model predictive control methodology, a cooperative planning approach is proposed by decomposing the augmented Lagrangian formulation of the joint intermodal freight transport planning problem into subproblems that are then cooperatively solved by the IFTOs through iterative exchange of planning information. A simulation study on cooperative intermodal freight transport planning illustrates the potential of the proposed cooperative planning approach.**

I. Introduction

To reduce freight transport costs and the environmental and social effects of freight transport, intermodal freight transport has been used in practice and investigated in scientific research for several decades [1]. Intermodal freight transport innovates in the sense that better freight transport performance (e.g., lower transport costs, less environmental and social effects, etc.) are obtained by integrating the use of multiple modes of transport (e.g., trucks, trains, barges, etc.) over an intermodal freight transport network (IFTN) and an intensive use of information and communication technology (ICT) in the freight delivery process.

Intermodal freight transport operators (IFTOs) provide freight transport services by managing their own or hired transport capacities, e.g., transport vehicles, freight handling equipment, etc. At the operational level, the container flow management is done in a short time scale (e.g., hourly) by controlling container flows that leave each intermodal terminal and that change from one modality to another modality within each intermodal terminal taking into account the dynamic changes of transport demands, intermodal freight transport network properties, and traffic conditions in the network. For intermodal freight transport in a large IFTN, multiple IFTOs can be involved in the freight delivery process. Each IFTO controls container flows in a subnetwork while taking into account the interactions of container flows from neighboring subnetworks. To minimize the total freight delivery cost in the whole network and retain the independent operation capability of the IFTOs, they need to control container flows in a cooperative way while considering information privacy.

Distributed model predictive control (DMPC) is a general control methodology that can deal with control problems arising in practice due to the organizational couplings among different parties involved in a common task, the limited measurement ability and control access of different parties, and the different, possibly conflicting, objectives of different parties, etc. Detailed reviews of DMPC are presented in [2]–[4]. DMPC has been used in the control of different types of transport networks. A DMPC framework was applied for the signaling split control of urban traffic networks [5]. These traffic networks are represented by linear dynamic systems and combined together by with local input constraints. The paper [6] presented a DMPC scheme to maintain water levels of irrigation canals close to certain pre-specified reference values considering disturbances. DMPC has also been studied in the control of power networks for different network scenarios and control purposes, the frequency control of a multiple high-voltage-direct-current link power network [7], [8], and the power flow management of a mixed energy network integrating renewable energy sources [9].

The current paper models intermodal freight transport from a container flow perspective and investigates the cooperative intermodal freight transport planning problem among multiple IFTOs over their subnetworks belonging to a large IFTN. A multi-agent cooperative intermodal freight transport planning approach is proposed using the DMPC structure for controlling container flows by multiple IFTOs in their subnetworks in order to minimize the overall freight delivery cost for serving certain transport demands. Adopting the DMPC scheme proposed in [8], the cooperative planning approach is derived by decomposing the augmented Lagrangian formulation [10], [11] of the joint intermodal freight transport planning problem into subproblems for each IFTO. IFTOs cooperatively solve their subproblems in a parallel fashion through iterative exchange of planning information. Multi-agent-based approaches have been used for modeling and managing freight transport in literature [12], [13]. An approach using basic Lagrangian relaxation for minimizing lateness of delivery (of individual containers) to end users in multimodal corridors has recently been proposed in [14].

This paper is structured in the following way. Section II presents the cooperative intermodal freight transport problem setting studied in this paper. Based on the authors' earlier work [15], the dynamics of single intermodal freight transport subnetwork are formulated in Section III. Section IV presents our proposed multi-agent cooperative intermodal freight transport planning approach in detail. A simulation study comparing the proposed cooperative planning approach with a centralized transport planning approach is provided in Section V. Section VI concludes the paper and gives future research directions.

L. Li and B. De Schutter are with the Delft Center for Systems and Control, Delft University of Technology, Delft, The Netherlands; e-mail: {L.Li-1,b.deschutter}@tudelft.nl. R.R. Negenborn is with the Department of Marine and Transport Technology, Delft University of Technology, Delft, The Netherlands; e-mail: r.r.negenborn@tudelft.nl.

II. A cooperative intermodal freight transport planning problem

We consider intermodal freight transport in a large IFTN defined by a directed graph $\mathcal{G}(\mathcal{V},\mathcal{E},\mathcal{M})$ that is a combination of N_{s} subnetworks. The sets $\mathcal{V}$, $\mathcal{E}$, and $\mathcal{M}$ are the node set, the link set, and the transport mode and modality change[1] set of the network, respectively. A link[2] $(i,j,m) \in \mathcal{E}$, denoted by $l_{i,j}^m$, implies that container flows can move from node $i \in \mathcal{V}$ to node $j \in \mathcal{V}$ with either using transport mode $m \in \mathcal{M}$ or performing modality change $m \in \mathcal{M}$. For transport demands in the whole network, their origin and destination pairs and their volume for time step k are given by the set $\mathcal{O}_{\mathrm{od}} \subseteq \mathcal{V}\times\mathcal{V}$ and $d_{o,d}(k)$, $(o,d) \in \mathcal{O}_{\mathrm{od}}$, respectively.

Subnetwork $\mathcal{G}_n(\mathcal{V}_n,\mathcal{E}_n,\mathcal{M}_n)$ is with $\mathcal{V}_n \subseteq \mathcal{V}$, $\mathcal{E}_n \subseteq \mathcal{E}$, $\mathcal{M}_n \subseteq \mathcal{M}$, and $n \in \{1,\ldots,N_{\mathrm{s}}\}$. All subnetworks are non-overlapping subnetworks with $\mathcal{V}_n \cap \mathcal{V}_m = \varnothing$, $\mathcal{E}_n \cap \mathcal{E}_m = \varnothing$, $n \in \{1,\ldots,N_{\mathrm{s}}\}$, $m \in \{1,\ldots,N_{\mathrm{s}}\}$, $n \neq m$. Each subnetwork n has a set of neighboring subnetworks, a set of incoming interconnection links, and a set of outgoing interconnection links. These three sets are denoted by $\mathcal{N}_n^{\mathrm{nb}}$, $\mathcal{E}_n^{\mathrm{in}}$, $\mathcal{E}_n^{\mathrm{out}}$, respectively. The set of neighboring subnetworks, $\mathcal{N}_n^{\mathrm{nb}}$, contains each subnetwork that has at least one transport connection with subnetwork n. Each outgoing interconnection link, $l_{i,j}^m \in \mathcal{E}_n^{\mathrm{out}}$, is considered to belong to subnetwork n and connects with one of its neighboring subnetworks in the set $\mathcal{N}_n^{\mathrm{nb}}$. Each incoming interconnection link $l_{i,j}^m \in \mathcal{E}_n^{\mathrm{in}}$ connects with subnetwork n, but is considered to belong to one of its neighboring subnetworks. The link set $\mathcal{E}_n$ comprises two types of links: local links $l_{i,j}^m \in \mathcal{E}_n \setminus \mathcal{E}_n^{\mathrm{out}}$, and outgoing interconnection links $l_{i,j}^m \in \mathcal{E}_n^{\mathrm{out}} \subseteq \mathcal{E}_n$.

For a multi-agent cooperative intermodal freight transport planning setting, each IFTO is modeled as an agent. Figure 1 illustrates a multi-agent cooperative intermodal freight transport planning setting for three IFTOs (agents). For each container flow with an origin and destination pair $(o,d) \in \mathcal{O}_{\mathrm{od}}$ that could move through the subnetwork n,

(i) Agent n determines its intermodal freight transport plans with the dynamic model of subnetwork n and its planning objective;
(ii) On the one hand, the dynamics of subnetwork n is influenced by container flows entering this subnetwork through all of its incoming interconnection links $l_{i,j}^m \in \mathcal{E}_n^{\mathrm{in}}$, and consequently by the dynamics of all of the neighboring subnetworks in the set $\mathcal{N}_n^{\mathrm{nb}}$ and container flow control decisions made by neighboring agents. On the other hand, container flows leaving subnetwork n through its outgoing interconnection links $l_{i,j}^m \in \mathcal{E}_n^{\mathrm{out}}$, also influence the dynamics of the neighboring subnetworks and the corresponding container flow control decisions.

[1] In intermodal freight transport, multiple modes of transport are available, and containers can change from one single-modal terminal to another single modal terminal with a different modality at the same intermodal terminal.

[2] In this paper 'm' in the superscript of a symbol refers to either one mode of transport or one type of modality change, e.g., $l_{i,j}^m$, and 'm' in the subscript of a symbol refers to a subnetwork e.g., $\mathcal{V}_m$.

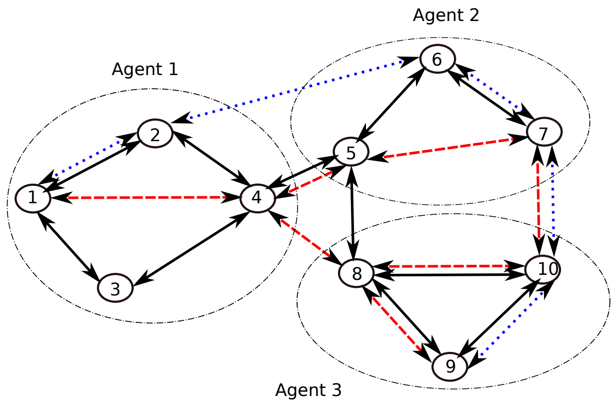

Fig. 1. A multi-agent cooperative intermodal freight transport planning setting for three IFTOs (agents). For simplicity, the modality change is not shown at intermodal terminals in this figure. Each of these three agents makes intermodal freight transport plans in a subnetwork indicated by dash-dotted black ellipses.

In a non-cooperative case, each agent n solves its own intermodal freight transport planning problem while assuming container flows from other neighboring subnetworks are known or can be estimated. In a cooperative case, each agent n first *computes* in a parallel fashion, and *optimizes* not only its container flow control decisions, but also container flows entering and leaving subnetwork n from and to subnetwork m, $m \in \mathcal{N}_n^{\mathrm{nb}}$. Next, agent n informs its neighboring agents of its preferred volumes of incoming and outgoing container flows from and to them. After that, each agent n repeats the optimization while taking into account the preferred incoming and outgoing container flow information from its neighboring agents in a cooperative way. Through a number of iterations, all agents *obtain their own* container flow control decisions while coming to an agreement on the volumes of incoming and outgoing container flows from and to their neighboring subnetworks. This paper consider the full cooperative intermodal freight transport planning among multiple IFTOs.

III. Dynamics of a single subnetwork

This section is derived from the dynamic IFTN model proposed in [15] by the authors. We refer to the paper [15] for a detailed explanation of variables and parameters in the network dynamics. We define a set $\mathcal{F}_n$ that contains any origin and destination pair $(o,d) \in \mathcal{O}_{\mathrm{od}}$ of container flows that could move through the subnetwork n. The discrete-time dynamics of subnetwork n with T_{s} (h) as the time step size is formulated as follows:

$$
\begin{aligned}
x_{i,o,d}(k+1) = x_{i,o,d}(k) + &\sum_{(j,m)\in\mathcal{N}_i^{\mathrm{in}}} y_{j,i,o,d}^m(k)T_{\mathrm{s}} \\
&- \sum_{(j,m)\in\mathcal{N}_i^{\mathrm{out}}} u_{i,j,o,d}^m(k)T_{\mathrm{s}} + d_{i,o,d}^{\mathrm{in}}(k)T_{\mathrm{s}} \\
&- d_{i,o,d}^{\mathrm{out}}(k)T_{\mathrm{s}}, \forall (o,d)\in\mathcal{F}_n, \forall i \in \mathcal{V}_n, \\
&\forall m \in \mathcal{M}_n, \forall k, \qquad (1)
\end{aligned}
$$

$$y^m_{i,j,o,d}(k) = \sum_{\substack{k_e = k - t^{m,\max}_{i,j} \\ k_e + t^m_{ij}(k_e) = k}}^{k-1} u^m_{i,j,o,d}(k_e), \forall (i,j,m) \in \mathcal{E}_n, \quad \forall (o,d) \in \mathcal{F}_n, \forall k, \tag{2}$$

$$x^m_{i,j,o,d}(k+1) = x^m_{i,j,o,d}(k) + \big(u^m_{i,j,o,d}(k) - y^m_{i,j,o,d}(k)\big) T_s, \quad \forall (i,j,m) \in \mathcal{E}_n, \forall (o,d) \in \mathcal{F}_n, \forall k, \tag{3}$$

$$\rho^{\text{truck}}_{i,j}(k) = \frac{L_{\text{truck}}}{L_{\text{oth}}} \left(\sum_{(o,d)\in\mathcal{F}_n} \frac{1}{L^{\text{truck}}_{i,j} \lambda^{\text{truck}}_{i,j}} x^{\text{truck}}_{i,j,o,d}(k) \right) + \rho^{\text{truck,oth}}_{i,j}(k), \tag{4}$$

$$v^{\text{truck,truck}}_{i,j}(k) = v^{\text{truck,truck}}_{i,j,\text{free}} \cdot \exp\left[-\frac{1}{a^{\text{truck,truck}}_{i,j}} \left(\frac{\rho^{\text{truck}}_{i,j}(k)}{\rho^{\text{truck}}_{i,j,\text{crit}}} \right)^{a^{\text{truck,truck}}_{i,j}} \right], \tag{5}$$

$$t^{\text{truck}}_{i,j}(k) = \textbf{round}\left(\frac{L^{\text{truck}}_{i,j}}{v^{\text{truck,truck}}_{i,j}(k)} \frac{1}{T_s} \right), \tag{6}$$

$$\sum_{(o,d)\in\mathcal{F}_n} \sum_{(j,m)\in\mathcal{N}^{\text{in}}_i} y^m_{j,i,o,d}(k) \le h^{\text{in}}_i, \forall i \in \mathcal{V}_n, \forall k, \tag{7}$$

$$\sum_{(o,d)\in\mathcal{F}_n} x_{i,o,d}(k) \le S_i, \forall i \in \mathcal{V}_n, \forall k, \tag{8}$$

$$\sum_{(o,d)\in\mathcal{F}_n} \sum_{(j,m)\in\mathcal{N}^{\text{out}}_i} u^m_{i,j,o,d}(k) \le h^{\text{out}}_i, \forall i \in \mathcal{V}_n, \forall k, \tag{9}$$

$$\sum_{(o,d)\in\mathcal{F}_n} x^m_{i,j,o,d}(k) \le C^m_{i,j}, \forall (i,j,m) \in \mathcal{E}_n, \forall k, \tag{10}$$

$$\sum_{(o,d)\in\mathcal{F}_n} u^m_{i,j,o,d}(k) \le C^{m,\text{in}}_{i,j}, \forall (i,j,m) \in \mathcal{E}_n, \forall k, \tag{11}$$

where

- For container flow with an origin and destination pair $(o,d) \in \mathcal{F}_n$ and for time step k, $x_{i,o,d}(k)$ (TEU[3]) and $x^m_{i,j,o,d}(k)$ (TEU) are the number of containers staying at node $i \in \mathcal{V}_n$ and in link $l^m_{i,j} \in \mathcal{E}_n$; $u^m_{i,j,o,d}(k)$ (TEU/h) is the container flow entering link $l^m_{i,j}, (j,m) \in \mathcal{N}^{\text{out}}_i$ where the set $\mathcal{N}^{\text{out}}_i$ contains all outgoing links of node i in subnetwork n; $y^m_{j,i,o,d}(k)$ (TEU/h) is the container flow leaving link $l^m_{j,i}, (j,m) \in \mathcal{N}^{\text{in}}_i$ where the set $\mathcal{N}^{\text{in}}_i$ consists of all incoming links of node i in the *whole* network; $d^{\text{in}}_{i,o,d}(k)$ (TEU/h) is the container flow entering node $o = i \in \mathcal{V}_n$ from the outside of the whole network; $d^{\text{out}}_{i,o,d}(k)$ (TEU/h) is the container flow arriving at the node $d = i \in \mathcal{V}_n$; $t^m_{i,j}(k)T_s$ (h) and $t^{m,\max}_{i,j}T_s$ (h) are the transport time and the maximum transport time on link $l^m_{i,j} \in \mathcal{E}_n$.
- For freeway link $l^{\text{truck}}_{i,j} \in \mathcal{E}_n$ and for time step k, $\rho^{\text{truck,truck}}_{i,j}(k)$ and $\rho^{\text{truck,oth}}_{i,j}(k)$ are the freight truck traffic density and the other traffic density that is not induced by intermodal freight truck transport; $L^{\text{truck}}_{i,j}$ (km) and $\lambda^{\text{truck}}_{i,j}$ are the length and the number of lanes of the link; $v^{\text{truck,truck}}_{i,j}(k)$ (km/h) and $t^{\text{truck}}_{i,j}(k)$ (h) are the average speed and the average transport time of container flow on the link; $v^{\text{truck,truck}}_{i,j,\text{free}}$, $a^{\text{truck,truck}}_{i,j}$ and $\rho^{\text{truck,truck}}_{i,j,\text{crit}}$ are the model parameters in the fundamental diagram model. The typical lengths of freight trucks and other vehicles are denoted by L_{truck} (m) and L_{oth} (m), respectively.
- The interactions of subnetwork n with neighboring subnetworks is explained in Section IV.
- For node $i \in \mathcal{V}_n$, h^{in}_i (TEU/h), h^{out}_i (TEU/h), and S_i (TEU) are the maximal container unloading and loading rates of the equipment and the storage capacity.
- For link $l^m_{i,j} \in \mathcal{E}_n$, $C^m_{i,j}$ (TEU) and $C^{m,\text{in}}_{i,j}$ (TEU/h) are the transport or modality change capacity and the maximal volume of container flows that can enter this link for each time step.

[3]In the container shipping, TEU stands for twenty-foot equivalent units.

IV. MULTI-AGENT COOPERATIVE INTERMODAL FREIGHT TRANSPORT PLANNING

In this section, we adopt the DMPC scheme introduced in [8] to derive a multi-agent cooperative intermodal freight transport planning approach in detail.

A. MPC of container flows for a single IFTO

In this section, IFTO (agent) n adopts a MPC approach for container flow control in subnetwork n. The whole planning period is N_{plan} time steps with N_p time steps as the prediction horizon. At each time step k, agent n solves an optimization problem to determine container flow control actions over a prediction horizon from time step k to $k + N_p - 1$ considering the dynamics and local constraints of subnetwork n, and its interactions with neighboring subnetworks. A sequence of control actions is obtained for the current prediction horizon and only the control actions obtained for time step k are implemented by agent n. After that, the optimization repeats for the next time step $k+1$ with an update of the subnetwork dynamics, transport demands, the interactions with neighboring subnetworks. For notational convenience, the optimization problem solved by agent n for the time step k is formulated as follows:

$$\begin{aligned}
&\min_{\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{y}}_n(k+1)} J_n\big(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{y}}_n(k+1)\big) \\
&= \sum_{(o,d)\in\mathcal{F}_n} w_{o,d} \Bigg[\sum_{l=1}^{N_p-1} \Bigg[\sum_{i\in\mathcal{V}_n} x_{i,o,d}(k+l) T_s \cdot \big(\alpha + C_{i,\text{store}}(k+l)\big) \\
&\quad + \sum_{(i,j,m)\in\mathcal{E}_n} x^m_{i,j,o,d}(k+l) T_s \big(\alpha + C^m_{i,j,\text{tran}}(k+l)\big) \Bigg] \\
&\quad + \sum_{i\in\mathcal{V}_n} x_{i,o,d}(k+N_p)\big(\alpha r_{i,d} + c_{i,d}\big) \\
&\quad + \sum_{(i,j,m)\in\mathcal{E}_n} x^m_{i,j,o,d}(k+N_p)\big(\alpha r^{m,d}_{i,j} + c^{m,d}_{i,j}\big) \Bigg]
\end{aligned} \tag{12}$$

subject to

$$\mathbf{x}_n(k+1+l) = \mathbf{f}_{\mathbf{1},n}\Big(\mathbf{x}_n(k+l), \mathbf{u}_n(k+l), \mathbf{d}_n(k+l), \mathbf{v}_n(k+l)\Big), \tag{13}$$

$$\mathbf{y}_n(k+1+l) = \mathbf{f}_{\mathbf{2},n}\Big(\mathbf{x}_n(k+1+l), \mathbf{u}_n(k+l), \mathbf{d}_n(k+l), \mathbf{v}_n(k+l)\Big), \tag{14}$$

$$\text{for } l = 0, \ldots, N_\mathrm{p} - 1,$$

$$\mathbf{g}_n\left(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{d}}_n(k), \tilde{\mathbf{v}}_n(k), \tilde{\mathbf{y}}_n(k+1)\right) \leq \mathbf{0}, \tag{15}$$

$$\mathbf{x}_n(k) = \mathbf{x}_{n,k}, \tag{16}$$

$$\tilde{\mathbf{d}}_n(k) = \tilde{\mathbf{d}}_{n,k}, \tag{17}$$

$$\tilde{\mathbf{v}}_n(k) = \tilde{\mathbf{v}}_{n,k}, \tag{18}$$

where

- $\tilde{\mathbf{x}}_n(k+1)$ contains the number of containers at each node and in each link of subnetwork n and the container flow control decisions for each link $l_{i,j}^m \in \mathcal{E}_n$ in the previous $t_{i,j}^{m,\max}$ time steps for container flows with origin and destination pairs $\mathcal{F}_n$ for time step k over the prediction horizon from time step $k+1$ to $k+N_\mathrm{p}$.
- $\tilde{\mathbf{u}}_n(k)$ includes the container flow control decisions for each link $l_{i,j}^m \in \mathcal{E}_n$ for container flows with origin and destination pairs $\mathcal{F}_n$ for time step k over the prediction horizon from time step k to $k+N_\mathrm{p}-1$.
- $\tilde{\mathbf{y}}_n(k+1)$ contains the volume of container flows with origin and destination pairs $\mathcal{F}_n$ that leave the subnetwork n for time step k over the prediction horizon from time step $k+1$ to $k+N_\mathrm{p}$.
- $\tilde{\mathbf{v}}_n(k)$ contains the volume of container flows with origin and destination pairs $\mathcal{F}_n$ that enter into subnetwork n from its neighboring subnetworks for time step k over the prediction horizon from time step k to $k+N_\mathrm{p}-1$. In the cooperative freight transport planning case, agent n receives $\tilde{\mathbf{v}}_{n,k}$ from its neighboring agents by communication, and $\tilde{\mathbf{v}}_{n,k}$ can be negotiated among agent n and its neighboring agents, and will finally be determined by the neighboring agents for time step k.
- $\tilde{\mathbf{d}}_n(k)$ is the volume of container flows with origin and destination pairs $\mathcal{F}_n$ that enter into the subnetwork n from the outside of the whole network for time step k over the prediction horizon from time step k to $k+N_\mathrm{p}-1$ and are given by $\tilde{\mathbf{d}}_{n,k}$.
- $w_{o,d} \in (0,1]$ indicates the relative priority of the container flows with origin and destination pairs $(o,d) \in \mathcal{F}_n$ with $\sum_{(o,d)\in\mathcal{O}_\mathrm{od}} w_{o,d} = 1$.
- $C_{i,\mathrm{store}}(k)$ (€/TEU/h) is the storage cost at node $i \in \mathcal{V}_n$, and $C_{i,j,\mathrm{tran}}^m(k)$ (€/TEU/h) is the transport or modality change cost in link $l_{i,j}^m \in \mathcal{E}_n$.
- $r_{i,d}$ (h/TEU), $c_{i,d}$ (€/TEU), $r_{i,j}^{m,d}$ (h/TEU), and $c_{i,j}^{m,d}$ (€/TEU) are the typical transport times and the typical delivery costs for transporting containers from node $i \in \mathcal{V}_n$ or link $l_{i,j}^m \in \mathcal{E}_n$ to a destination node $d \in \mathcal{V}$ in the whole network, respectively. They can be determined from statistical data.
- α (€/h) is the conversion factor for converting transport times to the equivalent monetary cost.

The subnetwork dynamics (13)–(14) and the local constraints (15) are derived by reformulating (1)–(11) in Section III. Because of the existence of the nonlinear equations (5) and (6), the container flow control problem (12) for agent n is a nonlinear and non-convex optimization problem. The SNOPT v7.2-5 solver in TOMLAB Optimization Toolbox is used to solve the problem.

B. Joint intermodal freight transport planning problem

The incoming interconnection links and outgoing interconnection links among subnetworks cause the couplings in the subnetwork dynamics and subsequently the container flow control decisions. These couplings are captured by introducing input and output interconnecting variables and interconnecting constraints among the intermodal freight transport planning problems of neighboring agents. For subnetwork n, these two types of variables and constraints for time step k over the prediction horizon from time step k to $k+N_\mathrm{p}-1$ are defined as follows:

$$\tilde{\mathbf{w}}_{\mathrm{in},n}(k) = \tilde{\mathbf{v}}_n(k), \tag{19}$$

$$\tilde{\mathbf{w}}_{\mathrm{out},n}(k) = \mathbf{K}_n \tilde{\mathbf{y}}_n(k+1), \tag{20}$$

$$\tilde{\mathbf{w}}_{\mathrm{in},m,n}(k) = \tilde{\mathbf{w}}_{\mathrm{out},n,m}(k), \quad m \in \mathcal{N}_n^\mathrm{nb}, \tag{21}$$

$$\tilde{\mathbf{w}}_{\mathrm{out},m,n}(k) = \tilde{\mathbf{w}}_{\mathrm{in},n,m}(k), \quad m \in \mathcal{N}_n^\mathrm{nb}, \tag{22}$$

where $\tilde{\mathbf{w}}_{\mathrm{in},m,n}(k)$ and $\tilde{\mathbf{w}}_{\mathrm{out},m,n}(k)$ are the interconnecting input and output variables of the optimization problem (12) of agent n with respect to the optimization problem of its neighboring agent $m \in \mathcal{N}_n^\mathrm{nb}$ for time step k; $\mathbf{K}_n$ is an interconnecting output selection matrix that is designed in such a way that only output container flows variables from links $l_{i,j}^m \in \mathcal{E}_n^\mathrm{out}$ are selected; the interconnecting input constraints (21) state that container flows entering subnetwork n from a neighboring subnetwork m refer to the same container flows that leave subnetwork m to its neighboring subnetwork n, and the interconnecting output constraints (22) are defined in the same way.

For all N_s agents, a joint intermodal freight transport planning problem is defined by combining the optimization problems (12) of all agents while assuming the influence from neighboring agents in (18) is known, but including the definition of the interconnecting input variables and output variables (19)–(20) and the interconnecting constraints (21)–(22). For time step k, the joint intermodal freight transport planning problem is formulated as follows:

$$\min_{\substack{\tilde{\mathbf{u}}_1(k),\ldots,\tilde{\mathbf{u}}_{N_\mathrm{s}}(k)\\ \tilde{\mathbf{x}}_1(k+1),\ldots,\tilde{\mathbf{x}}_{N_\mathrm{s}}(k+1)\\ \tilde{\mathbf{y}}_1(k+1),\ldots,\tilde{\mathbf{y}}_{N_\mathrm{s}}(k+1)}} \sum_{\mathrm{n}=1}^{\mathrm{N_s}} J_n\big(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{y}}_n(k+1)\big) \tag{23}$$

subject to, for $n = 1, \ldots, N_\mathrm{s}$, the subnetwork dynamics (13)–(14), the local constraints (15), the initial state (16), the container flows from the outside of the network (17), and the interconnecting input constraints (21) of subnetwork n.

C. A multi-agent cooperative intermodal freight transport planning approach

Ideally, the joint intermodal freight transport planning problem (23) has to be decomposed into N_s subproblems and each subproblem n is solved by agent n only using its local variables $\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{y}}_n(k+1)$. However, the presence of interconnecting constraints (21) makes it impossible to decompose the joint planning problem (23). Therefore, an augmented Lagrangian formulation [11] of the joint planning problem (23) is formulated to deal with interconnection constraints by introducing additional linear and quadratic cost terms in the joint planning objective. The introduction of Lagrange multipliers for addressing constraints (21) can be interpreted as follows: the container flows that one agent wants to send to its neighboring agents are in general different from those that its neighboring agents prefer to accept; these differences, therefore, have to be considered in the objective functions of individual agents in order to minimize the overall container delivery cost.

By duality theory [10], [11], the augmented Lagrangian formulation of the joint planning problem (23) can be solved through an iterative procedure by: 1) first solving a minimization problem with fixed Lagrange multipliers obtained in the previous iteration or given by initial values; 2) then updating the Lagrange multipliers using the solution from solving the minimization problem [10], [11]. The iterative procedure finishes when the change of Lagrange multipliers at two successive iterations is below a small threshold. As was done in [8], the non-separable quadratic terms in the minimization problem can be approximated using the auxiliary problem principle [16]–[18], such that the minimization problem can be decomposed into a group of subproblems. Each subproblem can be solved by each agent using only its local variables. These agents solve their corresponding subproblems in a parallel fashion. Therefore, a multi-agent cooperative intermodal freight transport planning approach is proposed as follows:

(i) Start from time step $k = 0$.

(ii) Transport demands for the whole network $\mathcal{G}(\mathcal{V}, \mathcal{E}, \mathcal{M})$ over the prediction horizon from time step k to $k + N_\mathrm{p} - 1$ are estimated and sent to all agents. The typical transport times and the typical delivery costs information used in (12) are obtained from historical data and shared by all agents. For $n = 1, \ldots, N_\mathrm{s}$, agent n measures the state of subnetwork n, $\mathbf{x}_{n,k}$, and calculates $\tilde{\mathbf{d}}_{n,k}$ using the received transport demands information for its subnetwork.

(iii) Agents cooperatively solve their container flow control problems through an iterative procedure. This procedure implements in the following way:

(a) Initialize the iteration counter $s = 1$, the threshold ε and the maximum iteration number allowed $s_{\max}$ in the stopping criteria of the iteration procedure as a small positive value and a positive integer respectively, and the Lagrange multipliers $\tilde{\boldsymbol{\lambda}}^{(s)}_{\mathrm{in},m,n}(k)$, $\tilde{\boldsymbol{\lambda}}^{(s)}_{\mathrm{in},n,m}(k)$ as arbitrary values when $k = 0$ or as their values obtained by the iterative procedure during time step $k - 1$ (referring as *warm start*).

(b) For $n = 1, \ldots, N_\mathrm{s}$, agent n determines container flow control actions $\tilde{\mathbf{u}}^{(s+1)}_n(k)$ in subnetwork n and comes to an agreement on the value of interconnecting variables $\tilde{\mathbf{w}}^{(s+1)}_{\mathrm{in},m,n}(k)$ and $\tilde{\mathbf{w}}^{(s+1)}_{\mathrm{out},m,n}(k)$, $m \in \mathcal{N}^{\mathrm{nb}}_n$, by solving the subproblem (24) in a *parallel* fashion. Agents start to solve their subproblems simultaneously while using the previous values of the interconnecting input variables $\tilde{\mathbf{w}}^{(s)}_{\mathrm{in},n,m}$, the interconnecting output variables $\tilde{\mathbf{w}}^{(s)}_{\mathrm{out},n,m}$, and the Lagrange multipliers $\tilde{\boldsymbol{\lambda}}^{(s)}_{\mathrm{in},n,m}(k)$ received from agents $m \in \mathcal{N}^{\mathrm{nb}}_n$. When all agents finish solving their subproblems, they send the values of their interconnecting input and output variables $\tilde{\mathbf{w}}^{(s+1)}_{\mathrm{in},m,n}$ and $\tilde{\mathbf{w}}^{(s+1)}_{\mathrm{out},m,n}$ to neighboring agents, and move to the next substep (c). The subproblems solved by agent n is given by:

$$\begin{aligned}
\min_{\substack{\tilde{\mathbf{u}}_n(k),\tilde{\mathbf{x}}_n(k+1),\tilde{\mathbf{y}}_n(k+1)\\ \tilde{\mathbf{w}}_{\mathrm{in},m_{n,1},n}(k),\ldots,\tilde{\mathbf{w}}_{\mathrm{in},m_{n,|\mathcal{N}^{\mathrm{nb}}_n|},n}(k),\\ \tilde{\mathbf{w}}_{\mathrm{out},m_{n,1},n}(k),\ldots,\tilde{\mathbf{w}}_{\mathrm{out},m_{n,|\mathcal{N}^{\mathrm{nb}}_n|},n}(k)}}
& J_n\left(\tilde{\mathbf{x}}_n(k+1), \tilde{\mathbf{u}}_n(k), \tilde{\mathbf{y}}_n(k+1)\right) \\
& + \sum_{\mathrm{m}\in\mathcal{N}^{\mathrm{nb}}_{\mathrm{n}}} \Bigg[\begin{bmatrix} \tilde{\boldsymbol{\lambda}}^{(s)}_{\mathrm{in},m,n}(k) \\ -\tilde{\boldsymbol{\lambda}}^{(s)}_{\mathrm{in},n,m}(k) \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \tilde{\mathbf{w}}_{\mathrm{in},m,n}(k) \\ \tilde{\mathbf{w}}_{\mathrm{out},m,n}(k) \end{bmatrix} \\
& + \frac{c}{2} \left\| \begin{bmatrix} \tilde{\mathbf{w}}_{\mathrm{in,prev},n,m}(k) - \tilde{\mathbf{w}}_{\mathrm{out},m,n}(k) \\ \tilde{\mathbf{w}}_{\mathrm{out,prev},n,m}(k) - \tilde{\mathbf{w}}_{\mathrm{in},m,n}(k) \end{bmatrix} \right\|_2^2 \\
& + \frac{b-c}{2} \left\| \begin{bmatrix} \tilde{\mathbf{w}}_{\mathrm{in},m,n}(k) - \tilde{\mathbf{w}}_{\mathrm{in,prev},m,n}(k) \\ \tilde{\mathbf{w}}_{\mathrm{out},m,n}(k) - \tilde{\mathbf{w}}_{\mathrm{out,prev},m,n}(k) \end{bmatrix} \right\|_2^2 \Bigg]
\end{aligned} \tag{24}$$

where $\tilde{\mathbf{w}}_{\mathrm{in,prev},m,n}(k)$, $\tilde{\mathbf{w}}_{\mathrm{out,prev},m,n}(k)$, $\tilde{\mathbf{w}}_{\mathrm{in,prev},n,m}(k)$, and $\tilde{\mathbf{w}}_{\mathrm{out,prev},n,m}(k)$ are the previous information of interconnecting variables of the agent n and its neighboring agents $m \in \mathcal{N}^{\mathrm{nb}}_n$ computed at iteration $s - 1$, respectively. The parameter b is a positive scalar and penalizes the deviation of the values of interconnecting variables during two successive iterations.

(c) Update the Lagrange multipliers with the following equation:

$$\begin{aligned}
\tilde{\boldsymbol{\lambda}}^{(s+1)}_{\mathrm{in},m,n}(k) = {} & \tilde{\boldsymbol{\lambda}}^{(s)}_{\mathrm{in},m,n}(k) \\
& + c\left(\tilde{\mathbf{w}}^{(s+1)}_{\mathrm{in},m,n}(k) - \tilde{\mathbf{w}}^{(s+1)}_{\mathrm{out},n,m}(k)\right),
\end{aligned} \tag{25}$$

and send $\tilde{\boldsymbol{\lambda}}^{(s+1)}_{\text{in},m,n}(k)$ to the neighboring agent $m \in \mathcal{N}^{\text{nb}}_n$.

(d) Continue to the next iteration $s+1$ and repeat substeps $(b)-(c)$ in step (ii) until either one or both of the two stopping criteria are reached. These two stopping criteria are defined by:

$$s > s_{\max} \tag{26}$$

$$\left\| \begin{bmatrix} \tilde{\boldsymbol{\lambda}}^{(s+1)}_{\text{in},m_{1,1},1}(k) - \tilde{\boldsymbol{\lambda}}^{(s)}_{\text{in},m_{1,1},1}(k) \\ \vdots \\ \tilde{\boldsymbol{\lambda}}^{(s+1)}_{\text{in},m_{N_{\text{s}},|\mathcal{N}^{\text{nb}}_n|},N_{\text{s}}}(k) - \tilde{\boldsymbol{\lambda}}^{(s)}_{\text{in},m_{N_{\text{s}},|\mathcal{N}^{\text{nb}}_n|},N_{\text{s}}}(k) \end{bmatrix} \right\|_{\infty} \leq \varepsilon \tag{27}$$

where $s_{\max}$ is the maximum number of iterations allowed and $\|\cdot\|_{\infty}$ indicates the infinity norm. When the iteration stops, each agent n determines its container flow control decisions $\tilde{\mathbf{u}}^*_n(k)$. The index $m_{n_i,n}$ refers to the $n_i{}^{\text{th}}$ neighboring agent of agent n with $n_i \in \{1,\ldots,|\mathcal{N}^{\text{nb}}_n|\}$.

(iv) The container flow control decisions $\mathbf{u}^*_n(k), n \in \{1,\ldots,N_{\text{s}}\}$ are implemented by each agent.

(v) Update time step $k = k+1$ and move to step (ii). The cooperative transport planning approach finishes when $k = N_{\text{plan}} - 1$.

V. Simulation Study

This section implements and compares both a centralized planning approach and the proposed multi-agent cooperative transport planning approach for a cooperative intermodal freight transport planning problem with two IFTOs.

A. Problem setting

We consider a cooperative intermodal freight transport planning problem with two IFTOs in an IFTN given in Figure 2. Subnetwork 1 consists of 3 nodes, 6 modality change links, 1 barge transport link, and 1 truck transport link. Subnetwork 2 comprises 2 nodes and 1 modality change link. There are two interconnection links, $l^{\text{truck}}_{1^{\text{W}},2^{\text{W}}}$ and $l^{\text{truck}}_{1^{\text{R}},2^{\text{R}}}$, that both belong to subnetwork 1.

The network parameters are as follows: the link transport time[4] and cost are shown as the labels of each link in Figure 2; the typical transport time and cost between any two nodes are given in Table I; the typical transport time and cost for a link are the average of the corresponding typical transport times and costs of the two nodes of this link; the other traffic density that is not induced by intermodal freight container flows on link $l^{\text{truck}}_{1^{\text{R}},2^{\text{R}}}$ is given in Table II; the capacities of nodes and links are assumed to be unlimited; a transport demand with an origin and destination pair $(1^{\text{W}}, 2^{\text{R}})$ is given in Table II; the fundamental diagram model parameters in Eq. (5) are taken as $v^{\text{truck,truck}}_{i,j,\text{free}} = 120$ km/h, $a^{\text{truck,truck}}_{i,j} = 1.867$ and $\rho^{\text{truck,truck}}_{i,j,\text{crit}} = 33.5$ veh/km/lane. The planning parameters are as follows: the planning period is 8 (h); the prediction horizon in the optimization problem (12) is taken as 6 (h); the time step T_{s} is taken as 1 (h); the conversion factor α is chosen as 5 (€/h); the states of two subnetworks are initialized to be empty.

[4]Note that the load-dependent transport time on link $l^{\text{truck}}_{1^{\text{R}},2^{\text{R}}}$ is computed with Eq. (6) and shown in the label.

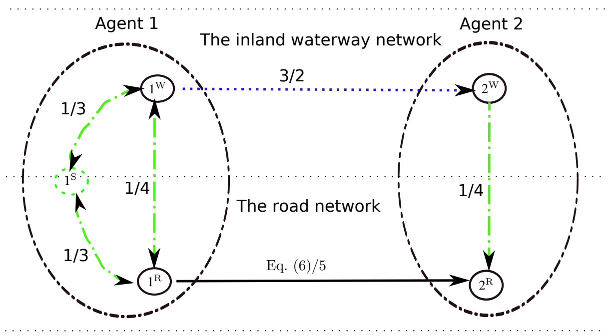

Fig. 2. An IFTN with 2 subnetworks.

TABLE I

The typical transport time $r_{i,d}$ (h) and 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

TABLE II

Densities of other traffic flows and transport demands

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

B. Cooperative intermodal freight transport planning

For the cooperative transport planning problem described in Section V-A, two planning approaches are investigated: a centralized planning approach and the proposed multi-agent cooperative intermodal transport planning approach.

For the centralized planning approach, we assume that there is only one IFTO that takes care of intermodal freight transport planning in the whole network. This IFTO also adopts the MPC approach for container flow control. This centralized planning scenario is the same scenario as been considered by authors in [19] with a receding horizon approach. The resulting total delivery cost is 40450€.

For the proposed multi-agent cooperative intermodal transport planning approach, the cooperation parameters are chosen as follows: $c = 0.1$, $b = 10c$, $\varepsilon = 10^{-1}$, and $s_{\max} = 250$. We assume that IFTO 1 and IFTO 2 are responsible for planning intermodal freight transport in subnetwork 1 and subnetwork 2, respectively. In the simulation, the cooperative planning approach selects not only the freeway route '1^{W} – 1^{R} – 2^{R}', but also the inland waterway route '1^{W} – 2^{W} – 2^{R}' in order to avoid the planning performance degradation when only the freeway route is used. The resulting delivery costs for agent 1 and agent 2 are 31458€ and 10214€,

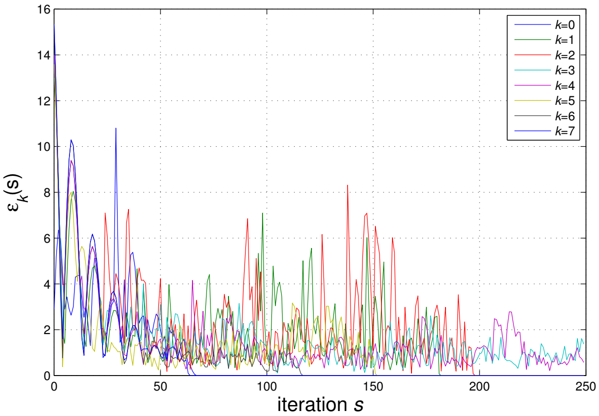

Fig. 3. The evolution of the instant value of stopping criterion $\varepsilon_k(s)$ for time step k.

respectively. Consequently, the resulting total delivery cost is 41672€, which is 3.02% higher than the centralized MPC planning approach.

The subnetwork dynamics in this paper contain nonlinear and non-convex relations. Therefore, in general the proposed cooperative planning approach in Section IV-C cannot be guaranteed to obtain the optimal planning performance. However, we see that the proposed cooperative planning approach obtains a planning performance that is almost the same as that of the centralized planning approach while taking a longer computation time in this particular simulation scenario. Note that the cooperative intermodal freight transport planning problem is distributed in nature and the relations between the planning performance obtained by and the computation time taken by the proposed multi-agent cooperative planning approach need further investigation. In this simulation study, the evolution of $\varepsilon_k(s)$ in the iteration procedure for time step k is shown in Figure 3. Due to the nonlinear and non-convex nature of the problem (24), the evolution of $\varepsilon_k(s)$ for time steps $k = 3$ and $k = 4$ demonstrates some fluctuations before the iteration procedure reaches the maximum iteration number defined in the stopping criterion (26).

VI. Conclusions and Future Work

The cooperative intermodal freight transport planning problem among multiple intermodal freight transport operators has been investigated in this paper. Based on a distributed model predictive control methodology, a multi-agent cooperative intermodal freight transport planning approach was proposed. The proposed cooperative planning approach performed nearly the same as the centralized planning approach in a particular simulation scenario. In the future, we will consider large-scale networks, and investigate other cooperative transport planning settings e.g., the cooperation of unimodal freight transport operators with different modalities in intermodal freight transport.

Acknowledgment

This research is supported by the China Scholarship Council under Grant 2011629027 and the VENI project "Intelligent multi-agent control for flexible coordination of transport hubs" (project 11210) of the Dutch Technology Foundation STW, a subdivision of the Netherlands Organization for Scientific Research (NWO).

References

[1] T. G. Crainic and K. H. Kim, "Intermodal transportation," in *Transportation*, ser. Handbooks in Operations Research and Management Science, C. Barnhart and G. Laporte, Eds. Elsevier, 2007, vol. 14, ch. 8, pp. 467–537.

[2] J. M. Maestre and R. R. Negenborn, Eds., *Distributed Model Predictive Control Made Easy*. Springer, 2014.

[3] R. Scattolini, "Architectures for distributed and hierarchical model predictive control– a review," *Journal of Process Control*, vol. 19, no. 5, pp. 723–731, May 2009.

[4] P. D. Christofides, R. Scattolini, D. M. de la Peña, and J. Liu, "Distributed model predictive control: A tutorial review and future research directions," *Computers & Chemical Engineering*, vol. 51, no. 0, pp. 21–41, 2013.

[5] L. B. de Oliveira and E. Camponogara, "Multi-agent model predictive control of signaling split in urban traffic networks," *Transportation Research Part C: Emerging Technologies*, vol. 18, no. 1, pp. 120–139, 2010.

[6] R. R. Negenborn, P.-J. van Overloop, T. Keviczky, and B. De Schutter, "Distributed model predictive control of irrigation canals," *Networks and Heterogeneous Media*, vol. 4, no. 2, pp. 359–380, 2009.

[7] P. Mc Namara, R. R. Negenborn, B. De Schutter, and G. Lightbody, "Optimal coordination of a multiple HVDC link system using centralized and distributed control," *IEEE Transactions on Control Systems Technology*, vol. 21, no. 2, pp. 302–314, 2013.

[8] R. R. Negenborn, B. De Schutter, and J. Hellendoorn, "Multi-agent model predictive control for transportation networks: Serial versus parallel schemes," *Engineering Applications of Artificial Intelligence*, vol. 21, no. 3, pp. 353–366, 2008.

[9] A. del Real, A. Arce, and C. Bordons, "An integrated framework for distributed model predictive control of large-scale power networks," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 1, pp. 197–209, Feb 2014.

[10] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, United Kingdom: Cambridge University Press, 2004.

[11] D. Bertsekas, *Constrained Optimization and Lagrange Multiplier Methods*. London, UK: Academic Press, 1982.

[12] P. Davidsson, L. Henesey, L. Ramstedt, J. Trnquist, and F. Wernstedt, "An analysis of agent-based approaches to transport logistics," *Transportation Research Part C: Emerging Technologies*, vol. 13, no. 4, pp. 255–271, 2005.

[13] J. Holmgren, P. Davidsson, J. A. Persson, and L. Ramstedt, "Tapas: A multi-agent-based model for simulation of transport chains," *Simulation Modelling Practice and Theory*, vol. 23, no. 0, pp. 1–18, 2012.

[14] A. Di Febbraro, N. Sacco, and M. Saeednia, "A cooperative framework for freight distribution in multimodal corridors," in *Proceedings of the 16th IEEE International Conference on Intelligent Transport Systems (ITSC 2013)*, Oct 2013, pp. 949–954.

[15] L. Li, R. R. Negenborn, and B. De Schutter, "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, Oct. 2013, pp. 1124–1230.

[16] J. Batut and A. Renaud, "Daily generation scheduling optimization with transmission constraints: A new class of algorithms," *IEEE Transactions on Power Systems*, vol. 7, no. 3, pp. 982–989, 1992.

[17] B. Kim and R. Baldick, "Coarse-grained distributed optimal power flow," *IEEE Transactions on Power Systems*, vol. 12, no. 2, pp. 932–939, 1997.

[18] C. Royo, *Generalized Unit Commitment by the Radar Multiplier Method*. Technical University of Catalonia, Barcelona, Spain: Ph.D thesis, 2001.

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