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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.
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 $N_n$ subnetworks. The sets $\mathcal{V}$, $\mathcal{E}$, and $\mathcal{M}$ are the node set, the link set, and the transport mode and modality set, respectively. A link $(i, j, m) \in \mathcal{E}$, 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 $\mathcal{O}_{od} \subseteq \mathcal{V} \times \mathcal{V}$ and $d_{o,d}(k), (o, d) \in \mathcal{O}_{od}$, respectively.

A 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 $n \in \{1, \ldots, N_n\}$. 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 $\mathcal{N}^{nb}_n$, $\mathcal{E}^{in}_n$, $\mathcal{E}^{out}_n$, respectively. The set of neighboring subnetworks, $\mathcal{N}^{nb}_n$, contains each subnetwork that has at least one transport connection with subnetwork $n$. Each outgoing interconnection link $l_{i,j}^m \in \mathcal{E}^{out}_n$, is considered to belong to subnetwork $n$ and connects with one of its neighboring subnetworks in the set $\mathcal{N}^{nb}_n$. Each incoming interconnection link $l_{i,j}^m \in \mathcal{E}^{in}_n$ 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 $l_{i,j}^m \in \mathcal{E}_n \setminus \mathcal{E}^{out}_n$, and outgoing interconnection links $l_{i,j}^m \in \mathcal{E}^{out}_n \subseteq \mathcal{E}_n$.

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 $(o, d) \in \mathcal{O}_{od}$ 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 other hand, the dynamics of subnetwork $n$ is influenced by container flows entering this subnetwork through all of its incoming interconnection links $l_{i,j}^m \in \mathcal{E}^{in}_n$, and consequently by the dynamics of all of the neighboring subnetworks in the set $\mathcal{N}^{nb}_n$ and container flow control decisions made by neighboring agents. On the other hand, container flows leaving subnetwork $n$ through its outgoing interconnection links $l_{i,j}^m \in \mathcal{E}^{out}_n$, also influence the dynamics of the neighboring subnetworks and the corresponding container flow control decisions.

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 $m$, $m \in \mathcal{N}^{nb}_n$. 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]. 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 $(o, d) \in \mathcal{O}_{od}$ 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:

$$x_{i,o,d}(k+1) = x_{i,o,d}(k) + \sum_{(j,m) \in \mathcal{N}^{in}_n} y_{i,j,o,d,k}^{in}(k)T_s$$

$$- \sum_{(j,m) \in \mathcal{N}^{out}_n} u_{i,j,o,d,k}^{out}(k)T_s + d_{i,o,d,k}^{in}(k)T_s$$

$$- d_{i,o,d,k}^{out}(k)T_s, \forall (o,d) \in \mathcal{F}_n, \forall i \in \mathcal{V}_n, \forall m \in \mathcal{M}_n, \forall k, \quad (1)$$

\[1\] 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., $\mathcal{V}_m$.\[2\]
where

\[ v_{i,j}^{\text{truck,free}}(k) = \sum_{k_n = k_{n-1} + \text{max}\left\{ v_{i,j}^{\text{truck,free}}(k_n), k_{n-1} \right\}}^{k_{n-1} + \text{max}\left\{ v_{i,j}^{\text{truck,free}}(k_n), k_{n-1} \right\}} u_{i,j,o,d}(k), \forall (i,j,m) \in \mathcal{E}_n, \forall k, \]

\[ x_{i,j,o,d}(k + 1) = x_{i,j,o,d}(k) + (u_{i,j,o,d}(k) - v_{i,j,o,d}(k)) T_s, \]

\[ \forall (i,j,m) \in \mathcal{E}_n, \forall (o,d) \in \mathcal{F}_n, \forall k, \]

\[ \rho_{i,j}^{\text{truck}}(k) = \frac{L_{\text{truck}}}{L_{\text{oth}}} \left( \sum_{(o,d) \in \mathcal{F}_n} \frac{1}{\rho_{i,j}^{\text{truck,oth}}(k)} \right) + \rho_{i,j}^{\text{truck,oth}}(k), \]

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

\[ n_{i,j}(k) = \text{round} \left( \frac{L_{i,j}^{\text{truck}}}{v_{i,j}^{\text{truck}}(k)} \right), \]

\[ \sum_{(o,d) \in \mathcal{F}_n} \sum_{(j,m) \in \mathcal{N}_{i,j}^{\text{in}}} y_{i,j,o,d}^{n}(k) \leq h_{i,j}^{\text{in}}, \forall i \in \mathcal{V}_n, \forall k, \]

\[ \sum_{(o,d) \in \mathcal{F}_n} x_{i,o,d}(k) \leq S_i, \forall i \in \mathcal{V}_n, \forall k, \]

\[ \sum_{(o,d) \in \mathcal{F}_n} u_{i,j,o,d}(k) \leq h_{i,j}^{\text{out}}, \forall i \in \mathcal{V}_n, \forall k, \]

\[ \sum_{(o,d) \in \mathcal{F}_n} x_{i,o,d}(k) \leq C_{i,j}^{\text{in}}, \forall (i,j,m) \in \mathcal{E}_n, \forall k, \]

\[ \sum_{(o,d) \in \mathcal{F}_n} u_{i,j,o,d}(k) \leq C_{i,j}^{\text{out}}, \forall (i,j,m) \in \mathcal{E}_n, \forall k, \]

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) and \(x_{i,j,o,d}(k)\) (TEU) are the number of containers staying at node \(i \in \mathcal{V}_n\) and in link \(l_{i,j}^{\text{in}}\) in \(\mathcal{E}_n\); \(u_{i,j,o,d}(k)\) (TEU/h) is the container flow entering link \(l_{i,j}^{\text{in}}\) \((j,m) \in \mathcal{N}_{i,j}^{\text{out}}\) where the set \(\mathcal{N}_{i,j}^{\text{out}}\) contains all outgoing links of node \(i\) in subnetwork \(n\); \(v_{i,j}^{\text{truck,free}}(k)\) is the container flow leaving link \(l_{i,j}^{\text{in}}\) \((j,m) \in \mathcal{N}_{i,j}^{\text{in}}\) where the set \(\mathcal{N}_{i,j}^{\text{in}}\) consists of all incoming links of node \(i\) in the whole network; \(v_{i,j}^{\text{truck}}(k)\) (TEU/h) is the container flow entering node \(i \in \mathcal{V}_n\) from the outside of the whole network; \(v_{i,j}^{\text{truck,free}}(k)\) (TEU/h) is the container flow arriving at the node \(i \in \mathcal{V}_n\); \(x_{i,j}^{\text{truck}}(k) T_s\) (h) and \(t_{i,j}^{\text{truck,free}}(k) T_s\) (h) are the transport time and the maximum transport time on link \(l_{i,j}^{\text{in}}\) \(\in \mathcal{E}_n\).

- For freeway link \(l_{i,j}^{\text{truck}} \in \mathcal{E}_n\) and for time step \(k\), \(\rho_{i,j}^{\text{truck}}(k)\) and \(\rho_{i,j}^{\text{truck,oth}}(k)\) are the freight truck traffic density and the other traffic density that is not induced by intermodal freight truck transport; \(L_{i,j}^{\text{truck}}\) (km) and \(\lambda_{i,j}^{\text{truck}}\) are the length and the number of lanes

3In 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 \(N_{\text{plan}}\) time steps with \(N_{\text{p}}\) 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 \(k + N_{\text{p}} - 1\) 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:

\[
\min_{\hat{x}_n(k+1), \hat{u}_n(k), \hat{y}_n(k+1)} J_n(\hat{x}_n(k+1), \hat{u}_n(k), \hat{y}_n(k+1))
\]

\[
= \sum_{(o,d) \in \mathcal{F}_n} w_{o,d} \left[ \sum_{l=1}^{N_{\text{p}}-1} \sum_{i \in \mathcal{V}_n} x_{i,o,d}(k+l) T_s \left( \alpha + C_{i,l,\text{store}}(k+l) \right) \right. \\
+ \sum_{(i,j,m) \in \mathcal{E}_n} x_{i,j}^{\text{in}}(k+l) T_s \left( \alpha + C_{i,j}^{\text{in}}(k+l) \right) \\
+ \sum_{e \in \mathcal{E}_n} x_{e}(k+N_{\text{p}}) \left( \alpha r_e + c_e \right) \\
+ \sum_{(i,j,m) \in \mathcal{E}_n} x_{i,j,o,d}(k+N_{\text{p}}) \left( \alpha r_{i,j}^{m,d} + c_{i,j}^{m,d} \right) \\
\]

(12)
subject to

\[
x_n(k + 1 + l) = f_{1,n}(x_n(k + l), u_n(k + l), d_n(k + l), v_n(k + l)), \quad l = 0, \ldots, N_p - 1,
\]

\[
y_n(k + 1 + l) = f_{2,n}(x_n(k + 1 + l), u_n(k + l), d_n(k + l), v_n(k + l)), \quad l = 0, \ldots, N_p - 1,
\]

\[
g_n \left(x_n(k + 1), \tilde{u}_n(k), \tilde{d}_n(k), \tilde{v}_n(k), \tilde{y}_n(k + 1) \right) \leq 0,
\]

where

- \(x_n(k + 1)\) contains the number of containers that the agent \(n\) will transport in the next time step.
- \(\tilde{u}_n(k)\) includes the container flow control decisions for agent \(n\) over the prediction horizon from time step \(k\) to \(k + N_p\).
- \(\tilde{v}_n(k)\) contains the volume of container flows to the neighboring subnetworks for agent \(n\) over the prediction horizon from time step \(k\) to \(k + N_p - 1\).
- \(\tilde{d}_n(k)\) includes the container flow control decisions for agent \(n\) over the prediction horizon from time step \(k\) to \(k + N_p\).
subject to, for \( n = 1, \ldots, N_s \), 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 \( \tilde{x}_n(k+1), \tilde{u}_n(k), \tilde{y}_n(k+1) \). 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 the previous iteration or given by initial values; and 3) then solving the subproblems using the solution from the previous iteration or given by initial values.

(a) Initialize the iteration counter \( s = 1 \), the threshold \( \varepsilon \) and the maximum iteration number allowed \( s_{\text{max}} \) in the stopping criteria of the iteration procedure as a small positive value and a positive integer respectively, and the Lagrange multipliers \( \tilde{\lambda}_{\text{in,}m,n}(k), \tilde{\lambda}_{\text{in,}n,m}(k) \) 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 \( n = 1, \ldots, N_s \), agent \( n \) determines container flow control actions \( \tilde{u}^{(s+1)}_{\text{in},m,n}(k) \) in subnetwork \( n \) and comes to an agreement on the value of interconnecting variables \( \tilde{w}^{(s+1)}_{\text{in,}m,n}(k) \) and \( \tilde{w}^{(s+1)}_{\text{out,}m,n}(k) \), \( m \in N_{nb}^n \), 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 \( \tilde{w}^{(s)}_{\text{in,}m,n} \), the interconnecting output variables \( \tilde{w}^{(s)}_{\text{out,}m,n} \), and the Lagrange multipliers \( \tilde{\lambda}^{(s)}_{\text{in,}n,m}(k) \) received from agents \( m \in N_{nb}^n \). When all agents finish solving their subproblems, they send the values of their interconnecting input and output variables \( \tilde{w}^{(s+1)}_{\text{in,}m,n} \) and \( \tilde{w}^{(s+1)}_{\text{out,}m,n} \) to neighboring agents, and move to the next substep (c). The subproblems solved by agent \( n \) is given by:

\[
\begin{align*}
\min & \quad \tilde{x}_n(k+1), \tilde{u}_n(k), \tilde{y}_n(k+1) \\
\text{s.t.} & \quad \sum_{m \in N_{nb}^n} \left[ \begin{array}{c} \tilde{\lambda}_{\text{in,}m,n}(k) \\ \tilde{\lambda}_{\text{in,}n,m}(k) \end{array} \right] \left[ \begin{array}{c} \tilde{w}_{\text{in,}m,n}(k) \\ \tilde{w}_{\text{out,}m,n}(k) \end{array} \right] \\
& \quad + \frac{c}{2} \left\| \tilde{w}_{\text{in,prev,}m,n}(k) - \tilde{w}_{\text{out,}m,n}(k) \right\|_2^2 \\
& \quad + \frac{b}{2} \left\| \tilde{w}_{\text{out,}m,n}(k) - \tilde{w}_{\text{out,prev,}m,n}(k) \right\|_2^2 \\
& \quad = 0 \\
& \quad \tilde{x}_n(k), \tilde{y}_n(k+1)
\end{align*}
\]

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

\[
\begin{align*}
\tilde{\lambda}_{\text{in,}m,n}^{(s+1)}(k) &= \tilde{\lambda}_{\text{in,}m,n}^{(s)}(k) \\
& \quad + c \left( \tilde{w}_{\text{in,}m,n}^{(s+1)}(k) - \tilde{w}_{\text{out,}m,n}^{(s+1)}(k) \right)
\end{align*}
\]
and send $\lambda_{m,m,n}^{(s+1)}(k)$ to the neighboring agent $m \in N_{nb}^n$.

(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:

$$s > s_{max}$$

$$\left\| \lambda_{m,m,1,1}^{(s+1)}(k) - \lambda_{m,m,1,1}^{(s)}(k) \right\| \leq \epsilon$$

$$\left\| \lambda_{m,m,x_{i},x_{j},1,x_{i}^{\text{lb}},N_{s}}^{(s+1)}(k) - \lambda_{m,m,x_{i},x_{j},1,x_{i}^{\text{lb}},N_{s}}^{(s)}(k) \right\| \leq \epsilon$$

(26)

(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 $\hat{u}_n^c(k)$. The index $m_{nb,n}$ refers to the $n_{th}$ neighboring agent of agent $n$ with $n_i \in \{1, \ldots, |N_{nb}^n|\}$.

(iv) The container flow control decisions $u_n^c(k), n \in \{1, \ldots, |N_n^s|\}$ 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, $l_{1W,2W}^{\text{track}}$ and $l_{1W,2W}^{\text{truck}}$, that both belong to subnetwork 1.

The network parameters are as follows: the link transport time 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 $l_{1W,2W}^{\text{track}}$ is given in Table II; the average of nodes and links are assumed to be unlimited; a transport demand with an origin and destination pair $(1W, 2R)$ is given in Table II; the fundamental diagram model parameters in Eq. (5) are taken as $v_{\text{truck}}^{\text{track}} = 120$ km/h, $a_{\text{truck}}^{\text{track}} = 1.867$ and $\rho_{\text{track,track}} = 33.5$ 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 $T_e$ is taken as 1 (h); the conversion factor $\alpha$ is chosen as 5 (€/h); the states of two subnetworks are initialized to be empty.

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: $c = 0.1, b = 10c, \epsilon = 10^{-1}$, 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 "1W – 1R – 2R", but also the inland waterway route "1W – 2W – 2R" 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€,

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Note that the load-dependent transport time on link $l_{1W,2W}^{\text{track}}$ is computed with Eq. (6) and shown in the label.
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.

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.

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References