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A Lagrangian Relaxation Heuristic Approach for Coordinated Global Intermodal Transportation

Wenjing Guo[1], Rudy R. Negenborn[2] and Bilge Atasoy[2]

Abstract— **This paper considers a coordinated global shipment matching problem in which a global operator receives shipment requests from shippers and three local operators provide local transport services in different geographical areas. While local operators make local matching decisions, the global operator combines the matched local services into itineraries to provide integrated transport for shipments. To handle the interconnecting constraints between different operators, a Lagrangian relaxation heuristic approach is developed. Under the proposed approach, the original problem is decomposed into local operator-related subproblems. These subproblems are optimized iteratively under local constraints as well as under the incentives imposed by the global operator to meet interconnecting constraints. The experiment results show that with the proposed approach, global transport planning that requires coordination among different operators to achieve a common goal can be realized.**

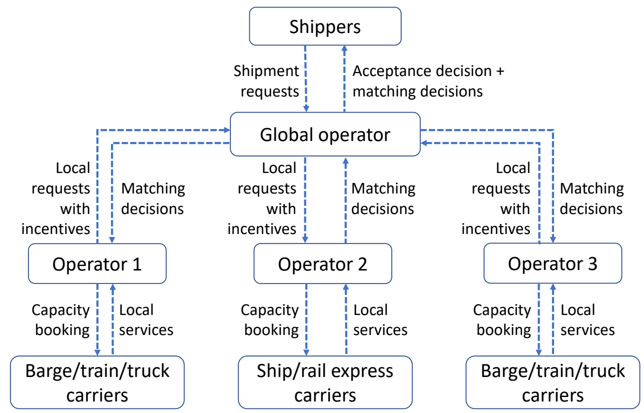

Fig. 1. Framework of coordinated global intermodal shipment matching.

I. INTRODUCTION

Global intermodal transportation is typically viewed as the provision of efficient, reliable, and flexible services through integrated planning for all the shipments involved in a global network under the control of a centralized system [1]. However, in practice, the operators of a global transport system are often geographically distributed, which makes it very difficult to apply a central controller to manage the whole system [2]. If players are not willing to give authority to a central controller, *distributed approaches* are needed to stimulate the cooperation among local operators [3]. Under such approaches, local operators have independent planning authority in their service networks and cooperate to achieve a common goal, such as increasing total profits, reducing the number of infeasible transshipments at interconnecting terminals, reducing delays in deliveries at destination terminals.

In this paper, we investigate a coordinated global intermodal shipment matching problem in which a platform owned by a global operator receives shipment requests from shippers and exchanges relevant information with local operators, as shown in Figure 1. Under such a platform, the global operator acts as an intermediary between shippers and local operators, to connect transport demand and supply without having direct control over these entities. Specifically, the global operator sends relative information of shipment requests to local operators and leaves the matching decisions with transport services to local operators. To stimulate local operators choosing the 'optimal' matching decisions that benefit the common goal, distributed approaches that handle interconnecting constraints need to be designed. After achieving consistency in matching decisions, the global operator combines the matched local services into itineraries to provide integrated transport for shipments. The coordination goal is hereby to maximize the total profits for accepting and matching shipment requests. The profit gain as a result of the collaboration needs to be shared among all the stakeholders to guarantee a win-win situation and fairness based on cooperative game theory [4]. In this paper, we focus on the coordinated transport planning problem and leave the profit sharing mechanism design to future research.

Although distributed approaches have been applied in many fields, such as power distribution networks [5], railway traffic management [6], vehicle platoons [7], inland intermodal freight transport chains [2], and hinterland intermodal container flow control [8], it is still challenging for global intermodal transportation which has different optimization models and interconnecting constraints from above studies. In the literature, the work of [8] is the most similar to this paper. It investigated a coordinated model predictive container flow control problem among multiple hinterland operators in different but interconnected service areas. These operators coordinate to reach an agreement on the volumes of container flows that each operator will hand over to other operators. Different from the work of [8], this paper focuses on global networks that have large time scales, four types of transport modes, and complex network typologies. Furthermore, we consider the coordination mechanism between a global operator and three local operators which have interconnected as well as overlapping subnetworks. In

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addition, this paper focuses on shipment requests that have specific time windows instead of container flows. Therefore, the interconnecting constraints include not only spatial compatibility but also time compatibility at interconnecting terminals. Besides, each request is rejectable, the consistency between acceptance decisions and matching decisions needs to be considered.

The contributions of this paper are listed as follow: (i) we introduce a coordinated shipment matching problem in global intermodal transportation; (ii) we develop mathematical models and interconnecting constraints to describe the problem; (iii) we develop a Lagrangian relaxation heuristic approach with lower bound settings to support coordination among a global operator and three local operators; (iv) we evaluate the performance of the approach under a real network.

The remainder of this paper is structured as follows. First, a detailed problem description is provided. We then present the mathematical formulation of coordinated global intermodal shipment matching. Next, the Lagrangian relaxation heuristic approach is developed to handle interconnecting constraints. After that, we conduct case study to investigate the performance of the proposed approach. Finally, the conclusions and future research directions are given.

II. Problem description

We consider a coordinated global intermodal shipment matching problem in which a global operator and three local operators cooperate to make acceptance and matching decisions for shipment requests, as shown in Figure 1. The global operator receives requests from shippers and makes acceptance decisions for each request. Each local operator receives part or all of the information of requests from the global operator and receives transport services from local carriers. Based on the local constraints (i.e., capacity limitation, time-spatial compatibility at transshipment terminals) and the incentives provided by the global operator, local operators make matching decisions with local services. After achieving consistency in matching decisions, each local operator books capacity on matched services from local carriers. The global operator combines the matched services into itineraries for each accepted shipment request.

Let $K = \{1, 2, 3\}$ be the set of local operators. Operator 1 is the hinterland operator in the export continent, operator 2 is the intercontinental operator, and operator 3 is the hinterland operator in the import continent. For example, operator 1 controls the hinterland network in Asia, operator 2 manages the intercontinental network connecting Asia and Europe, operator 3 controls the hinterland network in Europe.

Let $N = N^1 \cup N^2 \cup N^3$ be the set of terminals. Here, N^1 is associated with the export hinterland network that belongs to operator 1; N^2 corresponds to the intercontinental transport network; N^3 is the set of terminals in the import hinterland network that belongs to operator 3. Let N^{E} be the set of export terminals, $N^{\mathrm{E}} = N^1 \cap N^2$; let N^{I} be the set of import terminals, $N^{\mathrm{I}} = N^2 \cap N^3$. Let lt_i^m be the loading/unloading time with mode $m \in M = \{\text{ship, barge, train, truck}\}$ at terminal $i \in N$. We make a common assumption that the loading/unloading and storage capacity at terminals are unlimited [9].

Let $S = S^1 \cup S^2 \cup S^3$ be the set of transport services. Here, S^k is the set of services belongs to operator k. Each service $s \in S^k$ is characterized by its mode $m_s \in M$, origin terminal o_s, destination terminal d_s, free capacity U_s, departure time D_s, arrival time A_s, transport time t_s, and transport cost c_s. We consider ship, barge and train services as line services, namely, different services with the same mode might be operated by the same vehicle. We define l_{sq} equals to 0 if service s is the preceding service of service q, otherwise equals to 1. When $l_{sq} = 0$, transshipment operations are unnecessary. We consider each truck service as a fleet of trucks that have flexible departure times. We define D_{rs} as a variable that indicates the departure time of service $s \in S^{\text{truck}}$ with shipment $r \in R$.

Let R be the set of shipment requests. Each request $r \in R$ is characterized by its origin terminal $o_r \in N$, destination terminal $d_r \in N$, container volume u_r, announce time $\mathbb{T}_r^{\text{announce}}$ (i.e., the time when global operator receives the request), release time $\mathbb{T}_r^{\text{release}}$ (i.e., the time when the shipment is available for transport process), and fare class including freight rate p_r, lead time LD_r, and delay cost c_r^{delay}. The due time of request r is represented as, $\mathbb{T}_r^{\text{due}} = \mathbb{T}_r^{\text{release}} + LD_r$.

While the objective of the global operator is to maximize revenues by accepting requests, the objectives of local operators are to minimize total costs for matching requests with services. The coordinated common goal is to maximize the total profits based on total revenues and costs.

III. Coordinated global intermodal shipment matching

We first present the formulations for each operator. After that, we discuss the interconnecting constraints among multiple operators. Finally, we present the common goal of coordinated global intermodal shipment matching.

A. Mathematical model for the global operator

Let y_r be the binary variable which equals to 1 if request $r \in R$ is accepted, 0 otherwise. The objective of the global operator is to maximize total revenues received from shippers through acceptance decisions, presented as follows:

$$\textbf{P0-0} \quad \max_{\mathbf{y}} \sum_{r \in R} p_r u_r y_r \tag{1}$$

B. Mathematical model for local operator k

Let x_{rs} be the binary variable which is 1 if request $r \in R$ is matched with service $s \in S$. Let $\mathbb{T}_r^k$ be the delay of request r at its destination terminal $d_r \in N^k$. We define t_{ri}^- and t_{ri}^+ as the arrival and departure time of request $r \in R$ at export/import terminal $i \in N^{\mathrm{E}} \cup N^{\mathrm{I}}$. The objective of each local operator is to minimize total costs which consist of transportation costs and delay costs. The formulation for operator k is presented as follows:

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$$\textbf{P0-}k \quad \min_{\mathbf{x}} \sum_{r\in R}\sum_{s\in S^k} c_s x_{rs} u_r + \sum_{r\in R} c_r^{\text{delay}} \mathbb{T}_r^k u_r \tag{2}$$

subject to

$$\sum_{s\in S_i^{k-}} x_{rs} \le 1, \quad \forall r\in R, i\in N^k\backslash\{o_r\}, \tag{3}$$

$$\sum_{s\in S_i^{k+}} x_{rs} \le 1, \quad \forall r\in R, i\in N^k\backslash\{d_r\}, \tag{4}$$

$$\sum_{s\in S_{o_r}^{k-}} x_{rs} \le 0, \quad \forall r\in R, \tag{5}$$

$$\sum_{s\in S_{d_r}^{k+}} x_{rs} \le 0, \quad \forall r\in R, \tag{6}$$

$$\sum_{s\in S_i^{k+}} x_{rs} = \sum_{s\in S_i^{k-}} x_{rs}, \forall r\in R, i\in N^k\backslash\{o_r, d_r, N^{\text{E}}, N^{\text{I}}\}, \tag{7}$$

$$\sum_{r\in R} x_{rs} u_r \le U_s, \quad \forall s\in S^k, \tag{8}$$

$$\mathbb{T}_r^{\text{release}} + lt_{o_r}^{m_s} \le D_{rs} + \mathbf{M}(1-x_{rs}), \forall r\in R, s\in S_{o_r}^{k+\text{truck}}, \tag{9}$$

$$\mathbb{T}_r^{\text{release}} + lt_{o_r}^{m_s} \le D_s + \mathbf{M}(1-x_{rs}), \forall r\in R, s\in S_{o_r}^{k+}\backslash S_{o_r}^{k+\text{truck}}, \tag{10}$$

$$\begin{aligned} A_s + lt_i^{m_s} + lt_i^{m_q} \le D_q + \mathbf{M}(1-x_{rs}) + \mathbf{M}(1-x_{rq}),& \\ \forall r\in R, i\in N^k\backslash\{o_r, d_r\}, s\in S_i^{k-}\backslash S_i^{k-\text{truck}},& \\ q\in S_i^{k+}\backslash S_i^{k+\text{truck}}, l_{sq}=1,& \end{aligned} \tag{11}$$

$$\begin{aligned} D_{rs} + t_s + lt_i^{m_s} + lt_i^{m_q} \le D_q + \mathbf{M}(1-x_{rs}) + \mathbf{M}(1-x_{rq}),& \\ \forall r\in R, i\in N^k\backslash\{o_r, d_r\}, s\in S_i^{k-\text{truck}}, q\in S_i^{k+}\backslash S_i^{k+\text{truck}},& \end{aligned} \tag{12}$$

$$\begin{aligned} A_s + lt_i^{m_s} + lt_i^{m_q} \le D_{rq} + \mathbf{M}(1-x_{rs}) + \mathbf{M}(1-x_{rq}),& \\ \forall r\in R, i\in N^k\backslash\{o_r, d_r\}, s\in S_i^{k-}\backslash S_i^{k-\text{truck}}, q\in S_i^{k+\text{truck}},& \end{aligned} \tag{13}$$

$$\begin{aligned} D_{rs} + t_s + lt_i^{m_s} \le D_{rq} + \mathbf{M}(1-x_{rs}) + \mathbf{M}(1-x_{rq}),& \\ \forall r\in R, i\in N^k\backslash\{o_r, d_r\}, s\in S_i^{k-\text{truck}}, q\in S_i^{k+\text{truck}},& \end{aligned} \tag{14}$$

$$\begin{aligned} \mathbb{T}_r^k \ge A_s + lt_{d_r}^{m_s} - \mathbb{T}_r^{\text{due}} + \mathbf{M}(x_{rs}-1), \quad \forall r\in R,& \\ s\in S_{d_r}^{k-}\backslash S_{d_r}^{k-\text{truck}},& \end{aligned} \tag{15}$$

$$\begin{aligned} \mathbb{T}_r^k \ge D_{rs} + t_s + lt_{d_r}^{m_s} - \mathbb{T}_r^{\text{due}} + \mathbf{M}(x_{rs}-1), \quad \forall r\in R,& \\ s\in S_{d_r}^{k-\text{truck}},& \end{aligned} \tag{16}$$

$$\begin{aligned} t_{ri}^- \ge A_s + lt_i^{m_s} + \mathbf{M}(x_{rs}-1), \quad \forall r\in R,& \\ i\in N^{\text{E}}\cup N^{\text{I}}\backslash\{o_r, d_r\}, s\in S_i^{k-}\backslash S_i^{k-\text{truck}},& \end{aligned} \tag{17}$$

$$\begin{aligned} t_{ri}^- \ge D_{rs} + t_s + lt_i^{m_s} + \mathbf{M}(x_{rs}-1), \quad \forall r\in R,& \\ i\in N^{\text{E}}\cup N^{\text{I}}\backslash\{o_r, d_r\}, s\in S_i^{k-\text{truck}},& \end{aligned} \tag{18}$$

$$\begin{aligned} t_{ri}^+ \le D_q - lt_i^{m_q} + \mathbf{M}(1-x_{rq}), \quad \forall r\in R,& \\ i\in N^{\text{E}}\cup N^{\text{I}}\backslash\{o_r, d_r\}, q\in S_i^{k+}\backslash S_i^{k+\text{truck}},& \end{aligned} \tag{19}$$

$$\begin{aligned} t_{ti}^+ \le TD_{rq} - lt_i^{m_q} + \mathbf{M}(1-x_{rq}), \quad \forall r\in R,& \\ i\in N^{\text{E}}\cup N^{\text{I}}\backslash\{o_r, d_r\}, q\in S_i^{k+\text{truck}}.& \end{aligned} \tag{20}$$

Constraints (3-4) ensure that at most one service transports shipments departing from (arriving to) a node. Constraints (5-6) forbid matched services arriving to shipments' origins (departing from destinations). Constraints (7) ensure flow conservation at transshipment terminals. Constraints (8) represent capacity limitations. Constraints (9-14) ensure the time compatibility at transshipment terminals. Constraints (15-16) calculate delay time of request r at destination terminal. Constraints (17-18) calculate the arrival time at export and import terminals. Constraints (19-20) calculate the departure time at export and import terminals.

C. Interconnecting constraints

To ensure the feasibility of transport plan for each shipment, following interconnecting constraints must be met:

$$y_r \le \sum_{s\in S_{o_r}^{1+}} x_{rs} + \sum_{s\in S_{o_r}^{2+}} x_{rs} + \sum_{s\in S_{o_r}^{3+}} x_{rs}, \quad \forall r\in R, \tag{21}$$

$$y_r \le \sum_{s\in S_{d_r}^{1-}} x_{rs} + \sum_{s\in S_{d_r}^{2-}} x_{rs} + \sum_{s\in S_{d_r}^{3-}} x_{rs}, \quad \forall r\in R, \tag{22}$$

$$\begin{aligned} \sum_{s\in S_i^{1-}} x_{rs} + \sum_{s\in S_i^{2-}} x_{rs} = \sum_{s\in S_i^{1+}} x_{rs} + \sum_{s\in S_i^{2+}} x_{rs},& \\ \forall r\in R, i\in N^{\text{E}}\backslash\{o_r, d_r\},& \end{aligned} \tag{23}$$

$$\begin{aligned} \sum_{s\in S_i^{2-}} x_{rs} + \sum_{s\in S_i^{3-}} x_{rs} = \sum_{s\in S_i^{2+}} x_{rs} + \sum_{s\in S_i^{3+}} x_{rs},& \\ \forall r\in R, i\in N^{\text{I}}\backslash\{o_r, d_r\},& \end{aligned} \tag{24}$$

$$t_{ri}^- \le t_{ri}^+, \quad \forall r\in R, i\in N^{\text{E}}\backslash\{o_r, d_r\}, \tag{25}$$

$$t_{ri}^- \le t_{ri}^+, \quad \forall r\in R, i\in N^{\text{I}}\backslash\{o_r, d_r\}. \tag{26}$$

Constraints (21-22) ensure that request $r\in R$ will be transported by services departing from its origin o_r and arriving to its destination d_r if the request is accepted. Constraints (23-24) ensure flow conservation at import and export terminal for request $r\in R$. Constraints (25-26) ensure that the arrival time will be earlier than the departure time for each request $r\in R$ at export and import terminals.

D. Coordinated global intermodal shipment matching

The coordinated common goal is to maximize total profits which consists of revenues received from shippers, transport costs paid to carriers, and delay costs paid to shippers. The formulation of coordinated global intermodal shipment matching is presented as follows:

$$\begin{aligned} \textbf{P0} \quad \textbf{Z0} = \max_{\mathbf{y},\mathbf{x}} \sum_{r\in R} p_r u_r y_r& \\ - \sum_{k\in\{1,2,3\}} \left(\sum_{r\in R}\sum_{s\in S^k} c_s x_{rs} u_r + \sum_{r\in R} c_r^{\text{delay}} \mathbb{T}_r^k u_r \right)& \end{aligned} \tag{27}$$

subject to local constraints (3-20) for $k\in\{1,2,3\}$, and interconnecting constraints (21-26).

Since matching decisions are made by local operators independently with local information, model **P0** cannot be solved directly. To ensure the decisions made by local operators meet interconnecting constraints, distributed approaches are required.

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IV. Lagrangian relaxation heuristic approach

We develop a Lagrangian relaxation heuristic approach (LR-H) to stimulate cooperation between the global operator and three local operators. The main idea of the LR-H is to relax interconnecting constraints by bringing them into the objective function **Z0** with associated *Lagrangian multipliers* [5]. In this way, the original problem can be decomposed into four subproblems that relate to each operator. At each iteration, the global operator creates acceptance decisions based on the relaxed model and receives matching decisions from three local operators. If the interconnecting constraints cannot be met, the Lagrangian multipliers will be updated based on the proposed approaches. The process will be repeated until achieving a consistency on interconnecting constraints.

The LR-H approach is a relaxation method which penalizes violations of interconnecting constraints using a Lagrange multiplier, which imposes a cost on violations [5]. These added costs are used instead of the strict interconnecting constraints in the optimization. Specifically, we introduce Lagrangian multipliers $\lambda 1_r$, $\lambda 2_r$, $\lambda 3_{ri}$, $\lambda 4_{ri}$, $\lambda 5_{ri}$, $\lambda 6_{ri}$ to dualize interconnecting constraints (21), (22), (23), (24), (25), (26), respectively. While $\lambda 1_r$, $\lambda 2_r$, $\lambda 5_{ri}$, $\lambda 6_{ri}$ are non-negative values, $\lambda 3_r$ and $\lambda 4_r$ are unrestricted. The multipliers $\lambda 1_r$ can be interpreted as the prices paid to local operators for departing shipments from origin terminals. The multipliers $\lambda 2_r$ can be interpreted as the costs paid for delivering shipments to destination terminals. The multipliers $\lambda 3_{ri}$ and $\lambda 4_{ri}$ play as the penalty costs charged from local operators due to the violation of spatial compatibility at export and import terminals. The multipliers $\lambda 5_{ri}$ and $\lambda 6_{ri}$ play as the penalty costs charged from local operators due to the violation of time compatibility at export and import terminals. The formulation of the relaxed model is presented as follows:

$$
\begin{aligned}
\textbf{P1}\ \textbf{Z1} = & \max_{\mathbf{y},\mathbf{x}} \sum_{r\in R} p_r u_r y_r \\
& - \sum_{k\in\{1,2,3\}} \Big(\sum_{r\in R}\sum_{s\in S^k} c_s x_{rs} u_r + \sum_{r\in R} c_r^{\text{delay}} \mathbb{T}_r^k u_r\Big) \\
& + \sum_{r\in R} \lambda 1_r \Big(\sum_{s\in S_{o_r}^{1+}} x_{rs} + \sum_{s\in S_{o_r}^{2+}} x_{rs} + \sum_{s\in S_{o_r}^{3+}} x_{rs} - y_r\Big) \\
& + \sum_{r\in R} \lambda 2_r \Big(\sum_{s\in S_{d_r}^{1-}} x_{rs} + \sum_{s\in S_{d_r}^{2-}} x_{rs} + \sum_{s\in S_{d_r}^{3-}} x_{rs} - y_r\Big) \\
& + \sum_{r\in R}\sum_{i\in N^{\text{E}}} \lambda 3_{ri} \Big(\sum_{s\in S_i^{1+}} x_{rs} + \sum_{s\in S_i^{2+}} x_{rs} - \sum_{s\in S_i^{1-}} x_{rs} - \sum_{s\in S_i^{2-}} x_{rs}\Big) \\
& + \sum_{r\in R}\sum_{i\in N^{\text{I}}} \lambda 4_{ri} \Big(\sum_{s\in S_i^{2+}} x_{rs} + \sum_{s\in S_i^{3+}} x_{rs} - \sum_{s\in S_i^{2-}} x_{rs} - \sum_{s\in S_i^{3-}} x_{rs}\Big) \\
& + \sum_{r\in R}\sum_{i\in N^{\text{E}}\setminus\{o_r,d_r\}} \lambda 5_{ri} \left(t_{ri}^{+} - t_{ri}^{-}\right) \\
& + \sum_{r\in R}\sum_{i\in N^{\text{I}}\setminus\{o_r,d_r\}} \lambda 6_{ri} \left(t_{ri}^{+} - t_{ri}^{-}\right)
\end{aligned} \tag{28}
$$

subject to Constraints (3-20) for $k \in \{1,2,3\}$.

Model **P1** is easy to be decomposed into local operator-based subproblems.

We assume $(\mathbf{y}^*, \mathbf{x}^*)$ as the optimal solution of the original problem **P0**, $(\mathbf{y}^{**}, \mathbf{x}^{**})$ as the optimal solution of dual problem **P1**. However, the optimal solution of the dual problem might be infeasible to the original problem. Therefore, we transform the infeasible solution to a feasible solution by setting $y_r = 0, [x_{rs}] = [0]$ for request r if its transport plan is infeasible, and define $(\mathbf{y}, \mathbf{x})$ as the transformed feasible solution of the original problem. Based on the properties of Lagrangian relaxation, we can get $\mathbf{Z0}(\mathbf{y},\mathbf{x}) \le \mathbf{Z0}(\mathbf{y}^*,\mathbf{x}^*) \le \mathbf{Z1}(\mathbf{y}^*,\mathbf{x}^*) \le \mathbf{Z1}(\mathbf{y}^{**},\mathbf{x}^{**})$. We define $LB = \mathbf{Z0}(\mathbf{y},\mathbf{x})$ as the lower bound of the original problem, and define $UB = \mathbf{Z1}(\mathbf{y}^{**},\mathbf{x}^{**})$ as the upper bound of the original problem. When $UB = LB$, the obtained solution is the optimal solution to the original problem [3]. Therefore, the objective of the LR-H is to find the optimum Lagrangian multipliers that satisfy $UB = LB$.

Here, a standard subgradient method is used to update the Lagrangian multipliers, shown as follows:

$$
\begin{aligned}
\lambda 1_r^{n+1} = & \max\{0, \lambda 1_r^n + \rho 1_r^n (y_r - \sum_{s\in S_{o_r}^{1+}} x_{rs} - \sum_{s\in S_{o_r}^{2+}} x_{rs} \\
& - \sum_{s\in S_{o_r}^{3+}} x_{rs})\}, \quad \forall r\in R,
\end{aligned} \tag{29}
$$

$$
\begin{aligned}
\lambda 2_r^{n+1} = & \max\{0, \lambda 2_r^n + \rho 2_r^n (y_r - \sum_{s\in S_{d_r}^{1-}} x_{rs} - \sum_{s\in S_{d_r}^{2-}} x_{rs} \\
& - \sum_{s\in S_{d_r}^{3-}} x_{rs})\}, \quad \forall r\in R,
\end{aligned} \tag{30}
$$

$$
\begin{aligned}
\lambda 3_{ri}^{n+1} = & \lambda 3_{ri}^n + \rho 3_{ri}^n (\sum_{s\in S_i^{1-}} x_{rs} + \sum_{s\in S_i^{2-}} x_{rs} - \sum_{s\in S_i^{1+}} x_{rs} \\
& - \sum_{s\in S_i^{2+}} x_{rs}),\ \forall r\in R, i\in N^{\text{E}}\setminus\{o_r,d_r\},
\end{aligned} \tag{31}
$$

$$
\begin{aligned}
\lambda 4_{ri}^{n+1} = & \lambda 4_{ri}^n + \rho 4_{ri}^n (\sum_{s\in S_i^{2-}} x_{rs} + \sum_{s\in S_i^{3-}} x_{rs} - \sum_{s\in S_i^{2+}} x_{rs} \\
& - \sum_{s\in S_i^{3+}} x_{rs}),\ \forall r\in R, i\in N^{\text{I}}\setminus\{o_r,d_r\},
\end{aligned} \tag{32}
$$

$$
\begin{aligned}
\lambda 5_{ri}^{n+1} = & \max\{0.0001, \lambda 5_{ri}^n + \rho 5_{ri}^n (t_{ri}^{-} - t_{ri}^{+})\}, \\
& \forall r\in R, i\in N^{\text{E}}\setminus\{o_r,d_r\},
\end{aligned} \tag{33}
$$

$$
\begin{aligned}
\lambda 6_{ri}^{n+1} = & \max\{0.00015, \lambda 6_{ri}^n + \rho 6_{ri}^n (t_{ri}^{-} - t_{ri}^{+})\}, \\
& \forall r\in R, i\in N^{\text{I}}\setminus\{o_r,d_r\},
\end{aligned} \tag{34}
$$

where the superscript n is the iteration index used in the dual updating process; ρ^n is the step size at iteration n. To mitigate the issues of slow convergence, early stopping, and possible traps in local optimality, the step size parameters are updated as following strategy: $\rho^{n+1} = \theta 1 * \rho^n$ if $\lambda^{n+1} > \lambda^n$; $\rho^{n+1} = \theta 2 * \rho^n$ if $\lambda^{n+1} < \lambda^n$; $\theta 1 > 1$, $0 < \theta 2 < 1$; $\rho^{\min}$ is the minimum value of ρ; $\rho^{\max}$ is the maximum value. Regarding the minimum value of $\lambda 5_{ri}$ and $\lambda 6_{rj}$, the reason we give different positive values is to avoid the traps in generating the same infeasible departure/arrival times at export/import terminals.

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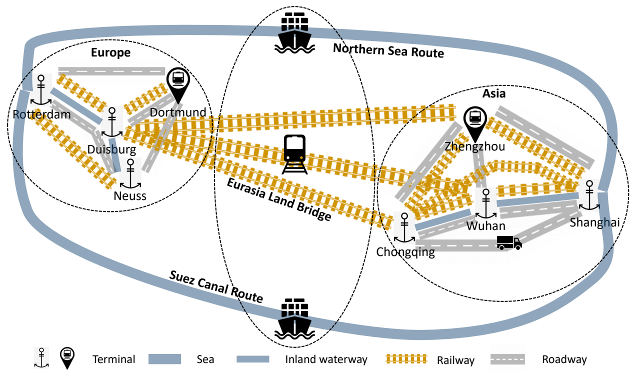

Fig. 2. Topology of a global intermodal network.

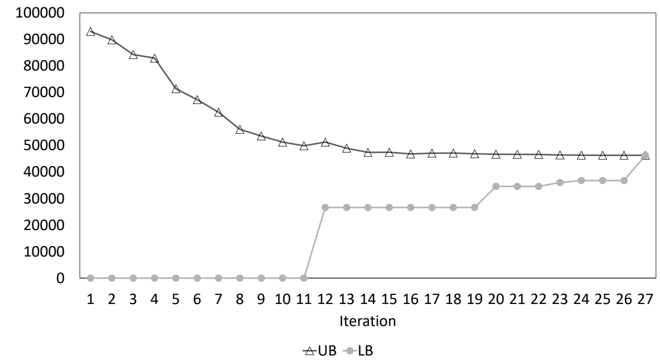

Fig. 3. Evolution of lower and upper bounds.

TABLE I

SHIPMENT REQUESTS.

Requests	Origin	Destination	Volume	Announce time	Release time	Due time	Delay cost	Freight rate
1	Chongqing	Rotterdam	9	0	89	569	25	5000
2	Wuhan	Dortmund	9	0	23	1103	12.5	2500
3	Zhengzhou	Dortmund	2	0	60	1140	12.5	2500
4	Chongqing	Neuss	1	0	119	1199	12.5	2500
5	Chongqing	Neuss	4	0	92	692	22.5	4500

Due to the non-convexity of the problem, we set lower bounds of departure time of truck service s with shipment r and lower bounds of departure time at export and import terminals under the LR-H. These lower bounds are updated based on infeasible solutions received at the current iteration. In this way, time variables can avoid the infeasible loop that when the Lagrangian multiplier is a positive value, the minimum value is always chosen as departure times; when the Lagrangian multiplier is a negative value, the maximum value is always chosen as departure times.

V. CASE STUDY

We evaluate the performance of the proposed LR-H approach in comparison to the centralized approach (CA) by [1]. The approaches are implemented in MATLAB, and the optimization problems are solved with CPLEX 12.6.3.

We use a global intermodal network which includes three subnetworks: a hinterland network in Asia, an intercontinental network connecting Asia and Europe, and a hinterland network in Europe, as shown in Figure 2. The Asian network includes one deep-sea port (i.e., Shanghai port) and three inland terminals (i.e., Zhengzhou, Wuhan, Chongqing); the European network includes one deep-sea port (i.e., Rotterdam port) and three inland terminals (i.e, Duisburg, Neuss, and Dortmund). The intercontinental network connects Asia and Europe by three routes: Northern Sea Route, Eurasia Land Bridge, and Suez Canal Route. We use 40 services of the Asian network, 52 services of the European network, and 14 services of the intercontinental network. At each terminal, the loading/unloading times (hours) are set as follows: $lt_i^{\text{ship}} = 12$, $lt_i^{\text{barge}} = 4$, $lt_i^{\text{train}} = 2$, $lt_i^{\text{truck}} = 1$ for $i \in N$. We design five shipment requests for the case study, as shown in Table I.

The algorithm parameters are set as follows: $[\rho 1] = [\rho 2] = [\rho 3] = [\rho 4] = [2500]$, $[\rho 5] = [\rho 6] = [0.001]$, $[\rho 1^{\min}] = [\rho 2^{\min}] = [\rho 3^{\min}] = [\rho 4^{\min}] = 10$, $[\rho 5^{\min}] = [\rho 6^{\min}] = [0.0001]$, $[\rho 5^{\max}] = [\rho 6^{\max}] = [0.01]$, $\theta 1 = 1$, $\theta 2 = 0.5$.

Figure 3 shows the evolution of the lower and the upper bound of the objective function in **P0** under the LR-H approach. It is easy to see that since all the initial Lagrangian multipliers are set as 0, the gap between the upper and lower bounds in the early stages is relatively large. However, it reduces rather quickly. At iteration 27, the upper bound equals the lower bound, which means the optimal solution under the LR approach has been found.

Regarding interconnecting constraints, we choose request 3 to analyze the coordination process. Figure 4 (a) shows that at initial iteration, when the Lagrangian multiplier $\lambda 1_3$ is 0, the global operator chooses to accept request 3, local operators do not arrange any services to transport request 3 leaving its origin terminal. Thus, conflicts happen between global and local operators. At iteration 2, the global operator increases the value of $\lambda 1_3$ to 2500. With this incentive, local operators arrange a service to transport request r leaving its origin terminal. Thereafter, the decisions made by the global operator and local operators are always consistent. Therefore, the global operator does not increase the price of $\lambda 1_3$ anymore. Similarly, Figure 4 (b) shows that after 5 iterations, the decision made by the global operator and local operators achieve consistency. The global operator chooses to accept request 3, local operators arrange a service to deliver request 3 to its destination terminal.

Figure 5(a) shows the evolution of the Lagrangian multiplier $\lambda 3$ and the differences between the value of inflow and outflow for request 3 at the export terminal. It is interesting to note that when the value of inflow is higher than outflow at the current iteration, the global operator increases the value of Lagrangian multiplier $\lambda 3$ at the next iteration; otherwise, the global operator decreases the values of Lagrangian multiplier $\lambda 3$ at the next iteration. It is also worth to note that the updates of Lagrangian multipliers become smaller as the iterations advance since the value of penalty parameter $\rho 3$ decreases when $\lambda 3^{n+1} > \lambda 3^n$. After 18 iterations, the value of inflow and outflow at Shanghai port achieves consistency. The similar trend is shown in Figure 5 (b). The consistency of inflow and outflow at the import terminal is achieved at iteration 23.

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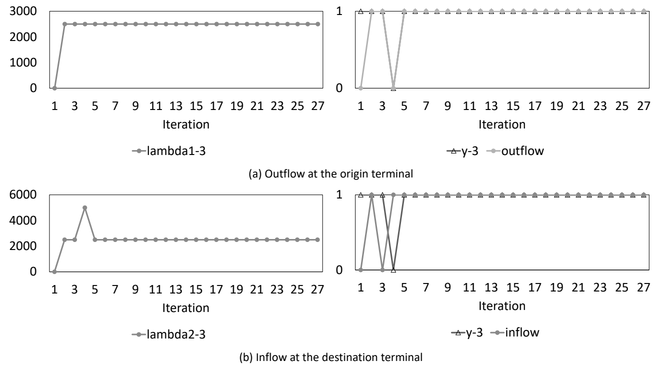

Fig. 4. Coordination process of Lagrangian multipliers ($\lambda 1_3$ and $\lambda 2_3$, left side) and interconnecting variables (acceptance decision y_3, outflow at the origin terminal, and inflow at destination terminal, right side) of request 3.

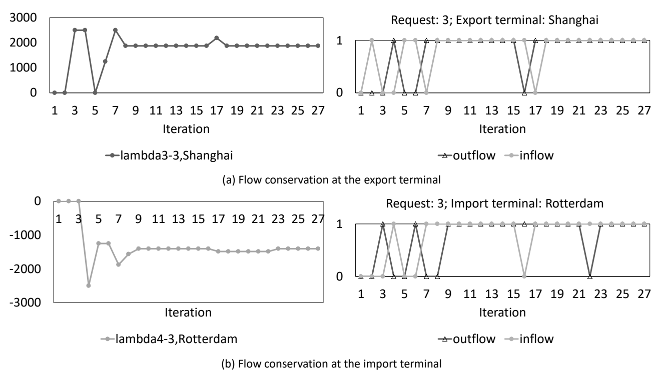

Fig. 5. Coordination process of Lagrangian multipliers ($\lambda 3_{3,\mathrm{Shanghai}}$ and $\lambda 4_{3,\mathrm{Rotterdam}}$, left side) and interconnecting variables (inflow and outflow at Shanghai and Rotterdam terminal, right side) of request 3.

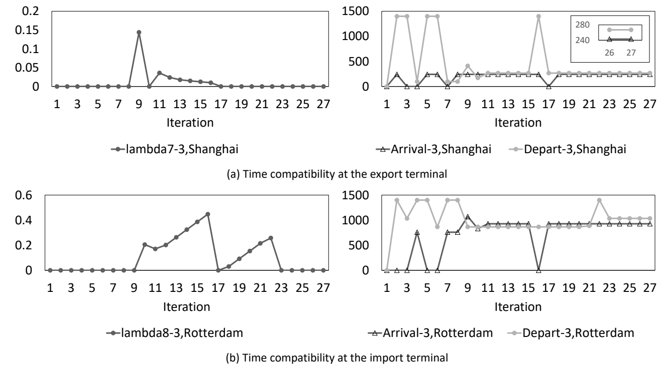

Fig. 6. Coordination process of Lagrangian multipliers ($\lambda 5_{3,\mathrm{Shanghai}}$ and $\lambda 6_{3,\mathrm{Rotterdam}}$, left side) and interconnecting variables (Arrival time t_{3i}^{-} and departure time t_{3i}^{+} at Shanghai and Rotterdam terminal, right side) of request 3.

Figure 6 (a) shows the evolution of Lagrangian multiplier $\lambda 5$ and the differences between the departure and arrival time at the export terminal. We notice that the value of Lagrangian multiplier $\lambda 5$ will be increased only when the value of the departure time is higher than the value of the arrival time at Shanghai port. After 19 iterations, the consistency on time compatibility at the export terminal is realized. Similarly, the consistency on time compatibility at the import terminal is achieved after 23 iterations.

Comparing Figure 4, Figure 5, and Figure 6, it is interesting to find that the value of decision variables is not only influenced by corresponding Lagrangian multipliers but also by other variables, i.e., even when the value of a Lagrangian multiplier stays the same, the value of corresponding decision variables might still change.

VI. Conclusions and Future Research

This paper investigated a coordinated shipment matching problem in global intermodal transportation. A Lagrangian relaxation heuristic (LR-H) approach was developed to stimulate the coordination between a global operator and three local operators. We used a global network to investigate the performance of the proposed approach. The experiment results showed that under the LR-H approach, coordinated global shipment matching can be realized with relatively small iterations of communications. In conclusion, with the proposed distributed approaches, global transport planning that requires coordination among different operators and synchronization in operations to achieve a common goal (e.g., increasing total profits) can be realized.

Our future research will focus on the following aspects: (1) investigating the performance of the LR-H under larger instances; (2) considering dynamic and stochastic scenarios for coordinated global shipment matching; (3) designing profit distribution mechanisms that ensure the fairness among stakeholders.

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