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THE EMPTY CONTAINER RELOCATION PROBLEM WITH FOLDABLE CONTAINERS IN THE HINTERLAND TRANSPORT OF A SEAPORT

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ABSTRACT

This study analyzes the impact of using foldable containers on cost savings of truck drayage operations of loaded and empty containers in the hinterland transportation of a seaport. We model a vehicle routing problem to optimize empty container relocation. A simulated annealing algorithm is developed for solving the problem. Numerical experiments are carried out with realistic empty container relocation scenarios. This study finds that, under certain conditions, foldable containers can significantly reduce the number of used trucks, trip length of truck haulage and the number of handlings compared to standard containers, and hence result in substantial cost savings.

Keywords: Container transportation; Empty container; Vehicle routing problem; Foldable container; Hinterland transportation

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1. INTRODUCTION

The container shipping industry has been witnessing an overwhelming growth and prosperity in recent decades. The Asian economic boom has been taking place since the 1990s. In the last few years, the Asian economy suffered from an economic crisis, but recently it has been recovering. Since large amounts of empty containers are being moved around the world at sea and over land, liner shipping companies face a challenge to effectively operate empty containers in both the sea- and land-legs. The cost structure of the total container transportation chain indicates that in particular the costs of the land-leg of the chain are high. The cost of hinterland transportation accounts on average for about 40% of the total container transportation costs, whilst both deep-sea shipping and port handling costs have a 30% share in the total cost (Notteboom and Winkelmans, 2001; Rabobank, 2004). Possibilities to save costs in empty container relocation are therefore worthy to study and have received considerable attention from both the industry and academia in recent years.

The current strategies to control the costs of repositioning empty containers are geared mainly to minimize the movements. However, it might be worthwhile to consider options that could reduce the costs of these movements. Foldable containers (FLDs) are expected to bring such cost reductions, as transportation capacity could be substantially enlarged if the mass of empty containers could shrink by using FLDs. Evidently, savings in transportation costs can only emerge if empty containers can be folded and packed together during their repositioning and if the journeys of drayage vehicles of container traffic in the hinterland is reorganized, for example, through linking different route legs. Although some tests have been carried out by liner companies to investigate the viability of FLDs for past years, they have not been introduced to the market in earnest yet.

Konings and Thijs (2001), Konings (2005) and Shintani et al. (2010) explored the savings that could potentially be realized by using FLDs in the land-leg of the entire container cargo distribution. However, they did not address the problem of the truck routing when delivering laden and empty containers in the hinterland. Since costs of empty container relocation in the land-leg are mainly associated with truck routing, that routing should be included in a discussion of the economic viability of FLDs. Therefore, this paper builds on these previous works to examine the cost-saving potential of FLDs in the land-leg by considering the truck routing. We model the (empty) container relocation problem (CRP) by trucks as a vehicle routing problem (VRP) to minimize the total costs of empty container relocation. Hereafter we refer to this combined concept of the problem as the container relocation with vehicle routing problem (CRVRP) for FLD usage. To solve this problem, we developed a simulated annealing (SA) algorithm-based meta-heuristic.

The rest of this paper is organized as follows. In the next section we present a brief literature review. The description of the CRVRP that includes the possibility to use two container types, i.e. FLD and standard container (STD), is given in Section 3. The mathematical formulations are given for the models. Section 4 contains an overview of

the SA-based meta-heuristic methods that we used for solving the problem. Experimental results are described in Section 5, whilst Section 6 contains concluding remarks.

2. RELATED STUDIES

We have structured our review of related studies according to the following classification of studies: CRP studies, VRP studies, CRVRP, and studies on foldable containers.

2.1 CRPs

Several studies have been published on the management of empty containers. Crainic et al. (1993) proposed dynamic and stochastic models for the CRP in a land-based transportation and distribution system. The objective of the CRP model is to determine the optimal distribution of empty containers that satisfies empty container demand and supply. Besides empty container demand and supply, repositioning empty containers in order to match empty container demand in future periods should also be considered. Jula et al. (2006) looked at the repositioning of empty containers from a different perspective; their aim was to reduce traffic congestion from heavy container truck traffic in the Los Angeles/ Long Beach port area. A network flow formulation was constructed to optimize empty container movements from consignees to shippers directly and/or via inland depots. Container relocation models are described among others in Chu (1995), Olivo et al. (2005), Di Francesco et al. (2006), and Chang et al. (2008). A detailed review of these and other empty container relocation problems can be found in Braekers et al. (2011).

2.2 VRPs on container haulage operations

Most studies of VRPs on haulage operations can be classified as full truckload pickup and delivery problems (Erera and Smilowitz, 2008). Related studies on the vehicle routing tend to extend the model variations mainly incorporating the time windows.

Gronalt et al. (2003) demonstrated possible cost savings using heuristics for a full truckload pickup and delivery problem with time windows (FT-PDPTW). Cargo is transported between distribution centers or depots. Vehicles are based at different depots and may perform several routes during the planning period. An FT-PDPTW with multiple vehicle depots and additional weight constraints in the context of log truck scheduling is studied by Gronalt and Hirsch (2007). Different variants of the tabu search meta-heuristic are proposed to solve the problem. Imai et al. (2007) introduced a full truckload pickup and delivery problem in the context of an intermodal terminal. Caris and Janssens (2009) extended this problem to an FT-PDPTW by including time window constraints at the customer locations.

2.3 CRVRPs

Dejax and Crainic (1987) already suggested that the independent consideration of

container relocation and vehicle routing neglects possible synergies arising from an integrated view on these problems. However, Crainic et al. (1993) stated that a single mathematical model comprising CRP and VRP would be computationally cumbersome. Recently, a number of attempts have been made to integrate CRP and VRP.

This study is closely related to Deidda et al. (2008) and Zhang et al. (2009). Deidda et al. (2008) proposed a static, deterministic optimization model that addresses the CRP between shippers, consignees and a port and the VRP for empty containers simultaneously. However, loaded container transportation is not considered. Vehicles are located at a single depot at the port and have a capacity of two containers. An exact algorithm is proposed. Zhang et al. (2009) studied CRVRP with vehicles that can carry only one container. A single container terminal and several vehicle depots with a stock of empty containers are considered. The objective is to minimize the total travel time. It is shown that the problem can be formulated as a multiple traveling salesman problem (m-TSP) with time windows and multiple depots. A reactive tabu search algorithm is proposed to solve the problem. Zhang et al. (2010) extended this problem to a multiple depot, multiple terminal problem and solved it with a time window partitioning method. Zhang et al. (2011b) investigated the single depot, single terminal problem where the number of empty containers available at the depot is limited.

Huth and Mattfeld (2009) compared the results of a sequential and integrated decision making approaches for allocating and routing swap bodies in a hub-and-spoke network. Vehicle routing decisions for both loaded and empty containers with a vehicle capacity of two containers are considered. The allocation problem is modeled as a multi-stage transportation problem whilst the routing problem is modeled as a generalization of the pickup and delivery problem. A large neighborhood search is used to solve the routing model in both the sequential and integrated approaches.

Baldacci et al. (2006) studied the multiple disposal facilities and multiple inventory locations for roll-on roll-off VRP. The problem arises in the sanitation industry where tractors move trailers between customer locations, disposal facilities, and inventory locations. A set partitioning formulation is used and an exact solution method is proposed.

Some integrated approaches for full truckload (haulage) problems with time windows have been proposed as well. Currie and Salhi (2004) proposed a tabu search heuristic for an FT-PDPTW with heterogeneous products and vehicles where the pickup points of goods to be delivered to customers are not predefined. The objective is to minimize the total cost, including a fixed cost per vehicle used. Smilowitz (2006) studied the routing and scheduling of loaded and empty trailers or containers in haulage operations. Trailer allocation decisions are made simultaneously with vehicle routing decisions by introducing flexible tasks for empty trailers demanded and supplied. The objective of the model is to minimize both fleet size and travel time. The model is solved by a branch-and-bound algorithm using column generation. Dynamic versions of this problem were studied by Escudero et al. (2011) and Zhang et al. (2011a). Another column generation approach embedded in a branch-and-bound framework for optimizing haulage operations of trailers

was proposed by Ileri et al. (2006). A heterogeneous fleet of drivers with different start and end locations is assumed. The objective is to minimize costs with company drivers having a different cost structure than third party drivers. Recently, Braekers et al. (2012) investigated a full truckload VRP for transporting loaded and empty containers in haulage operations. For empty container transportation, either the origin or the destination is not predefined. The problem is formulated as an asymmetric m-TSP with time windows.

2.4 Foldable containers

Few studies have explored the potential of repositioning with FLDs. Konings and Thijs (2001), and Konings (2005) addressed the economic and logistical viability of FLDs and have suggested some conditions under which they could be operated successfully. Konings (2005) argued and demonstrated that the savings that could be generated by FLDs are greater in the land-leg than in the sea-leg of the transportation chain. Although these studies are based on empirical data, they do not adequately reflect the complexity of container transportation chains. This shortcoming could be redressed by formulating and treating the problem as a network flow problem. Shintani et al. (2010) developed integer programming models to analyze the cost savings that could be achieved by using FLDs in the hinterland transportation. Zazgornik et al. (2012) built some different models for transporting wood in the timber transportation chain. They include log-trucks and FLDs. Tabu search-based algorithms were developed and implemented to solve the VRP, and combined vehicle routing and container scheduling problem. However, they investigated the FLDs for timber which are distributed in a simpler network than maritime containers. Shintani et al. (2012) found that savings could be realized in the management costs of container fleets by applying a proper combination of FLDs and STDs in the liner shipping route. They also showed that the economic viability of FLDs depends on the level of trade imbalances and the exploitation costs of the containers. Moon et al. (2013) compared the empty container repositioning costs of FLDs and STDs. The scope of their research is the ocean transportation in which empty containers are repositioned by vessels.

To the best of our knowledge, no studies have been reported to address the integrated problem of the VRP and CRP with FLDs for the hinterland transportation of the seaport. This paper refers to the existing CRP with FLDs by Konings and Thijs (2001), Konings (2005) and Shintani et al. (2010) to model the CRVRP with FLDs.

3. PROBLEM DESCRIPTIONS
3.1 Model outline

Following the study of Shintani et al. (2010), we define two scenarios regarding possible repositioning movements of empty containers to compare the total costs of FLDs and STDs, namely the direct exchange (DX) and the indirect exchange (IX) scenarios, which are implicitly reflected by truck routing. DX means that empty containers are directly transported from one customer to another, while IX implies that containers are

repositioned via an inland depot. Intuitively, it seems that IX leads to higher cost than DX. Although container shipping lines are increasingly encouraging the direct re-use of empty containers, the indirect relocation in the hinterland is more widely implemented for different practical reasons (e.g. liability issues, difficult match of demand and supply of container types).

The emphasis of this study is to show the advantage of using FLDs in terms of cost savings in truck routing of loaded and empty containers in the hinterland of the seaport. The advantage is demonstrated with comparisons of the objective function value of the optimal CRVRP solution with FLDs and the one with STDs, in which both types of containers are distributed in the hinterland for import and export.

In the CRVRP we consider the distribution of loaded and empty containers between a single inland depot and customers' sites. The models address the empty container repositioning from pickup (supply) points to delivery (demand) points by trucks, while satisfying transportation requests for loaded containers of import/export. Moreover, each customer handles multiple containers for import or export, and then the same vehicle may be assigned to several routes during a given working time. The models deal with a problem based on data regarding the supply of and demand for empty containers on a one day basis. The task of the models is to find optimal truck routing and empty container relocation in the hinterland in order to minimize the total costs.

For the STD these costs consist of:

 – Location-relocation costs: the costs of the movements of loaded and empty containers by trucks in the hinterland (mostly fuel costs).

 – Fixed costs: the fleet-related costs of trucks.

 – Handling costs: the costs of loading and unloading containers to/from trucks.

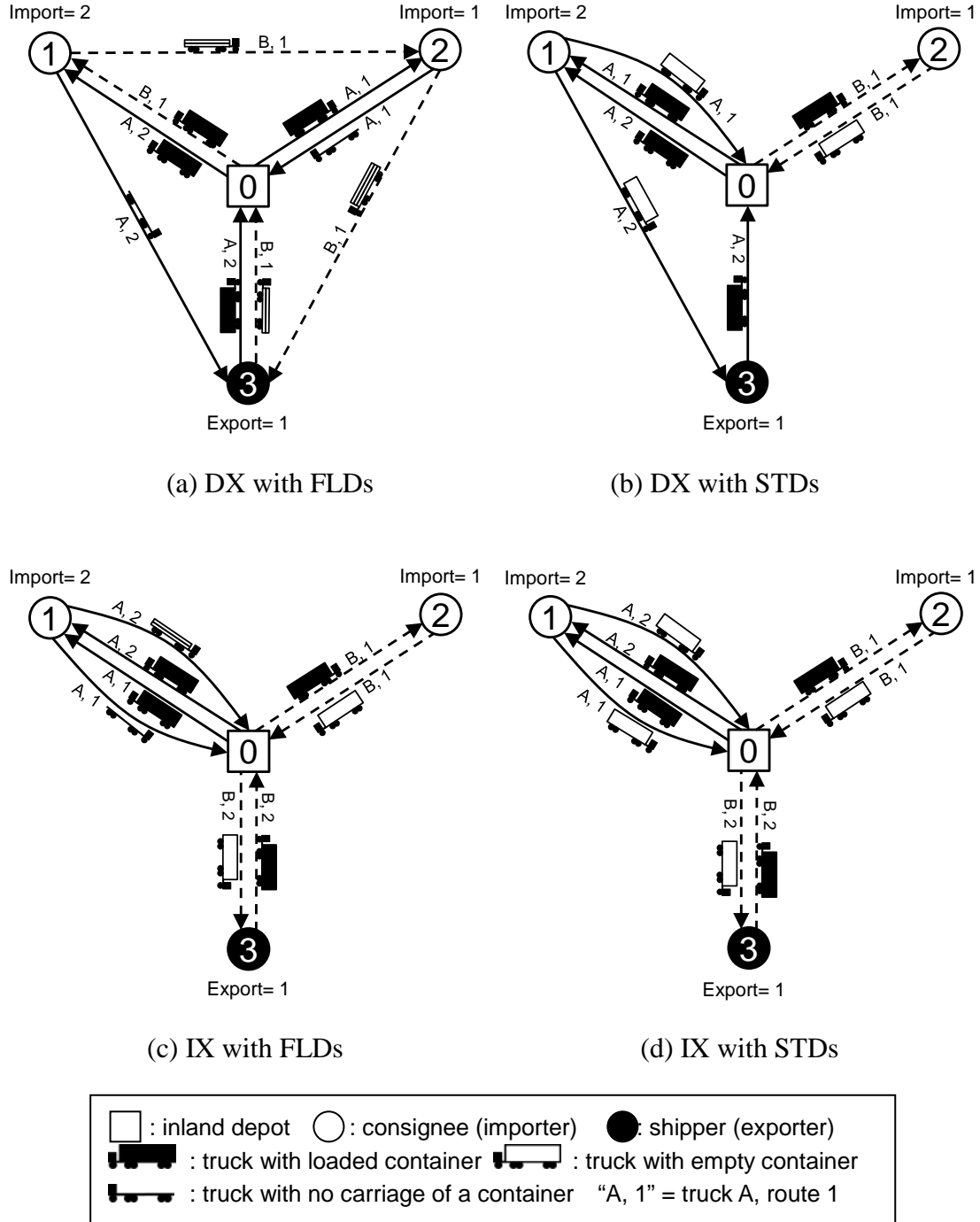 – Exploitation costs of the container.

For the FLD there are additional cost categories: folding and unfolding (F/UF) costs.

Since the CRVRP assumes two types of truck routing scenarios with two types of containers, empty containers are relocated through four types of truck drayage patterns as shown in Fig. 1, namely, DX with FLDs and STDs, IX with FLDs and STDs.

The definition of the truck routing scenarios DX and IX, and the difference between these scenarios are as follows:

(1) *Direct Exchange* (DX): empty containers are directly exchanged between customers where F/UF is possible at the customers' sites.

(2) *Indirect Exchange* (IX): empty containers are indirectly exchanged between customers via the inland depot and F/UF is possible at the customers' sites.

The more complex and less practiced scenario is DX. It assumes that unloaded (empty) containers at consignees' sites can be transported directly to shippers' sites to load these containers, however this empty movement is more restrictive. In practice it will be a barrier if consignees and shippers are served by different shipping lines, since a shipping line usually does not allow another shipping line to use their own containers, unless both of them share common agreements. Moreover, as Hanh (2003) discusses, real-time

(a) DX with FLDs   (b) DX with STDs

(c) IX with FLDs   (d) IX with STDs

☐ : inland depot   ◯ : consignee (importer)   ● : shipper (exporter)

🚚 : truck with loaded container   🚚 : truck with empty container

🚚 : truck with no carriage of a container   "A, 1" = truck A, route 1

Fig. 1 The difference of truck routing scenarios for container haulage

information on export containers is often not available at the time when import containers
become empty. Such restrictions could be mitigated to some extent if information systems
and co-operation among shipping lines in exchanging containers (the development of so
called "grey boxes") are improved and widely spread. In addition to the possible mismatch
in time there may be a mismatch in container types that are demanded and supplied, which
can also make direct re-use (IX) impossible.

    The CRVRP could be regarded as a consolidation of three kinds of VRPs, namely, the

VRP with pickup and delivery (VRPPD), the split delivery VRP (SDVRP), and the VRP with multiple use of vehicles (VRPM). The CRVRP is defined as follows:

Let $G = (N, A)$ be a complete and directed graph with node set $N = \{0, 1, \cdots, n\}$, where the node "0" represents the inland depot (all truck routes start from/end at 0), and all remaining nodes represent pickup points (or consignees) and delivery points (or shippers) of empty containers. The arc set is defined as $A = \{(i, j) | i, j \in N, i \neq j\}$. In the CRVRP a vehicle fleet with a homogeneous type of trucks must satisfy transportation requests.

3.2 Assumptions

The models are based on the following assumptions:

(a) The models consider both the pickup and delivery of loaded and empty containers in the hinterland based on data regarding the supply of and demand for empty containers on a one day basis. Thus each truck finishes pickup and delivery services within one day.

(b) Homogeneous containers in length are used: FLD and STD are both 40 feet long. This assumption excludes empty container movements that arise from a mismatch in supply and demand for type of containers. Moreover, this assumption limits the complexity of the problem formulation.

(c) In case of FLDs, up to four empties can be bundled into one unit, which corresponds to the size of a single STD.

(d) The exploitation cost of an FLD is estimated twice as high as the one of an STD, due to higher purchase, maintenance and repair costs.

(e) Empty containers at each site are transferred from consignees to the inland depot or are directly moved from consignees to shippers. Surplus containers, i.e., empty containers which cannot be reused in the hinterland, return from customers to the inland depot.

(f) The storage capacity at each site and the transportation capacity of each link connecting a specific site pair are assumed to be infinite.

(g) The storage costs of containers at each site are small enough to be ignored. These costs are marginal, especially when the planning horizon for empty container relocation is just one day.

(h) Empty containers, regardless of FLD or STD, are handled in the same manner when shipped to consignees from the places where they are stacked on the ground awaiting for the next shipment.

3.3 Formulations

In this paper, as mentioned above, we examine two scenarios DX and IX for empty container relocation with two container types FLD and STD. Regardless of container types, a single truck can only transport a single loaded container per trip.

In principle the definition of two scenarios for the two container types would require

four different integer programming (IP) models. Hence four model formulations are represented as follows:

[DX_FLD]: the CRVRP for DX with FLDs

[DX_STD]: the CRVRP for DX with STDs

[IX_FLD]: the CRVRP for IX with FLDs

[IX_STD]: the CRVRP for IX with STDs

3.3.1 Formulation for DX with FLDs

The model for this scenario is formulated as follows:

[DX_FLD]

Minimize

$$
\sum_{k\in K}\sum_{r\in R}\sum_{i\in N}\sum_{j\in N}C_{ij}^{T}X_{ij}^{kr} + C^{H}\sum_{k\in K}\sum_{r\in R}\sum_{i\in N}\left(2FH_{i}^{kr}+UH_{i}^{kr}\right)
$$
$$
+ C^{U}\left(\sum_{k\in K}\sum_{r\in R}\sum_{i\in N/\{0\}}U_{i}^{kr} - 2\sum_{k\in K}\sum_{r\in R}\sum_{i\in N/\{0\}}\sum_{j\in N/\{0\}}US_{ij}^{kr}\right) + C^{V}\cdot V + C^{FF}\cdot FF
$$
(1)

subject to

$$
\sum_{k\in K}\sum_{r\in R}\sum_{j\in N}X_{ij}^{kr}\geq 1 \quad \forall i\in N,
$$
(2)

$$
\sum_{k\in K}\sum_{r\in R}\sum_{i\in N}X_{ij}^{kr}\geq 1 \quad \forall j\in N,
$$
(3)

$$
\sum_{j\in N}X_{0j}^{kr}\leq 1 \quad \forall k\in K, r\in R,
$$
(4)

$$
\sum_{i\in N}X_{i0}^{kr}\leq 1 \quad \forall k\in K, r\in R,
$$
(5)

$$
\sum_{h\in N}X_{hi}^{kr} = \sum_{j\in N}X_{ij}^{kr} \quad \forall i\in N, k\in K, r\in R,
$$
(6)

$$
TT_{i}^{kr}+T_{ij}-M\left(1-X_{ij}^{kr}\right)\leq TT_{j}^{kr} \quad \forall i,j\in N/\{0\}, k\in K, r\in R,
$$
(7)

$$
\sum_{i\in N}\sum_{j\in N}T_{ij}X_{ij}^{kr}\leq L \quad \forall k\in K, r\in R,
$$
(8)

$$
\sum_{k\in K}\sum_{r\in R}FZ_{0j}^{kr}=D_{j} \quad \forall j\in N,
$$
(9)

$$
\sum_{k\in K}\sum_{r\in R}FZ_{i0}^{kr}=P_{i} \quad \forall i\in N,
$$
(10)

$$
\sum_{k\in K}\sum_{r\in R}\sum_{j\in N}EZ_{ij}^{kr} - \sum_{k\in K}\sum_{r\in R}\sum_{h\in N}EZ_{hi}^{kr} = D_{i}-P_{i} \quad \forall i\in N\setminus\{0\},
$$
(11)

$$
FZ_{ij}^{kr}\leq X_{ij}^{kr} \quad \forall i,j\in N, k\in K, r\in R,
$$
(12)

$$
EZ_{ij}^{kr}\leq 4X_{ij}^{kr} \quad \forall i,j\in N, k\in K, r\in R,
$$
(13)

53

$$EZ_{ij}^{kr} \le 4\left(1 - FZ_{ij}^{kr}\right) \quad \forall i \in N, j \in Q_i, k \in K, r \in R, \tag{14}$$

$$FH_i^{kr} = \sum_{j \in N} FZ_{ij}^{kr} \quad \forall i \in N, k \in K, r \in R, \tag{15}$$

$$-EH_i^{kr} \le \sum_{j \in N} EZ_{ij}^{kr} - \sum_{h \in N} EZ_{hi}^{kr} \le EH_i^{kr} \quad \forall i \in N, k \in K, r \in R, \tag{16}$$

$$\sum_{p=1}^{4} \left(p \cdot \delta_i^{krp}\right) = EH_i^{kr} \quad \forall i \in N, k \in K, r \in R, \tag{17}$$

$$\sum_{p=1}^{4} \delta_i^{krp} \le 1 \quad \forall i \in N, k \in K, r \in R, \tag{18}$$

$$UH_i^{kr} = \sum_{p=1}^{4} \delta_i^{krp} \quad \forall i \in N, k \in K, r \in R, \tag{19}$$

$$U_i^{kr} = EH_i^{kr} \quad \forall i \in N, k \in K, r \in R, \tag{20}$$

$$\sum_{p=1}^{4} \left(p \cdot \phi_{ij}^{krp}\right) = EZ_{ij}^{kr} \quad \forall i, j \in N, k \in K, r \in R, \tag{21}$$

$$\sum_{p=1}^{4} \phi_{ij}^{krp} \le 1 \quad \forall i, j \in N, k \in K, r \in R, \tag{22}$$

$$\eta_{ij}^{kr} = \left(1 - \sum_{h \in N} \sum_{p=1}^{4} \phi_{hi}^{krp}\right) + \phi_{ij}^{kr1} + \left(1 - \sum_{l \in N} \sum_{p=1}^{4} \phi_{jl}^{krp}\right)$$

$$\forall i, j \in N \setminus \{0\}, k \in K, r \in R, \tag{23}$$

$$\sum_{q=1}^{3} \left(q \cdot \lambda_{ij}^{krq}\right) = \eta_{ij}^{kr} \quad \forall i, j \in N \setminus \{0\}, k \in K, r \in R, \tag{24}$$

$$\sum_{q=1}^{3} \lambda_{ij}^{krq} \le 1 \quad \forall i, j \in N \setminus \{0\}, k \in K, r \in R, \tag{25}$$

$$US_{ij}^{kr} = \lambda_{ij}^{kr3} \quad \forall i, j \in N \setminus \{0\}, k \in K, r \in R, \tag{26}$$

$$FF = \sum_{i \in N} D_i, \tag{27}$$

$$V \le \left|N - \{0\}\right|, \tag{28}$$

$$\sum_{r \in R}\sum_{i \in N}\sum_{j \in N} X_{ij}^{kr} \leq M \cdot W^k \quad k \in K, \tag{29}$$

$$V = \sum_{k \in K} W^k, \tag{30}$$

$$FF, V \geq 0 \quad \text{and integer}, \tag{31}$$

$$TT_i^{kr} \geq 0 \quad \forall i \in N, k \in K, r \in R. \tag{32}$$

$$EH_i^{kr}, FH_i^{kr}, UH_i^{kr}, U_i^{kr} \geq 0 \quad \text{and integer} \quad \forall i \in N, k \in K, r \in R, \tag{33}$$

$$EZ_{ij}^{kr}, FZ_{ij}^{kr}, US_{ij}^{kr}, \eta_{ij}^{kr} \geq 0 \quad \text{and integer} \quad \forall i, j \in N, k \in K, r \in R, \tag{34}$$

$$W^k \in \{0,1\} \quad k \in K, \tag{35}$$

$$X_{ij}^{kr} \in \{0,1\} \quad \forall i, j \in N, k \in K, r \in R, \tag{36}$$

$$\delta_{ij}^{krp}, \phi_{ij}^{krp} \in \{0,1\} \quad \forall i, j \in N, k \in K, r \in R, p \in \{1,...,4\}, \tag{37}$$

$$\lambda_{ij}^{krq} \in \{0,1\} \quad \forall i, j \in N, k \in K, r \in R, q \in \{1,...,3\}. \tag{38}$$

where

K set of trucks

R set of truck routes

N set of inland depot and customers, that is $N = \{0,1,\cdots,n\}$, the vertex 0 represents the inland depot (all truck routes start from/end at 0) where n is the number of customers

Q_i subset of N where $Q_i \in \{j \mid j \neq 0, i = 0, \forall i, j \in N\} \cup \{j \mid j = 0, i \neq 0, \forall i, j \in N\}$

W^k =1 if truck k is used, =0 otherwise

X_{ij}^{kr} =1 if arc (i, j) is used by truck k on route r, =0 otherwise

FZ_{ij}^{kr} the number of loaded containers transported by truck k on route r from customer's sites i to j

EZ_{ij}^{kr} the number of empty containers transported by truck k on route r from customers' sites i to j

FH_i^{kr} the number of loading and unloading full containers to/from truck k on route r at customers' sites i

EH_i^{kr} the number of loading and unloading empty containers without being folded to/from truck k on route r at customers' sites i

UH_i^{kr} the number of loading and unloading empty containers with being folded to/from truck k on route r at customers' sites i

U_i^{kr} the number of F/UF containers to/from truck k on route r at customers' sites i

US_{ij}^{kr} the number of empty containers without being folded, transported by truck k on route r from customers' sites i to j

TT_i^{kr} traveling time at node i of truck k on route r

V truck fleet size

FF container fleet size of FLDs

$\delta_i^{krp}, \phi_{ij}^{krp}, \eta_{ij}^{kr}, \lambda_{ij}^{krq}$ auxiliary variables

M a sufficiency large constant

C_{ij}^T costs of the movements of empty containers by trucks from depot/customers'
sites i to j

C^H cost of loading and unloading containers to/from trucks at customers' sites

C^U cost of F/UF FLDs at the inland depot and customers' sites

C^V fleet-related cost of trucks

C^{FF} exploitation cost of FLD

D_i the number of empty container demand (imported containers) for pickup at
customers' sites i

P_i the number of empty containers demands (exporting containers) for delivery at
customers' sites i

L time capacity of trucks

T_{ij} traveling time of truck from customers' sites i to j

Notice that the following symbols are decision variables: X_{ij}^{kr} , FZ_{ij}^{kr} , EZ_{ij}^{kr} , FH_i^{kr} ,
$EH_i^{kr}, UH_i^{kr}, U_i^{kr}, US_{ij}^{kr}, TT_i^{kr}, V$.

The objective function (1) minimizes the total costs, which consist of the costs of the
movements of containers by trucks, the costs of loading and unloading containers to/from
trucks, F/UF costs at customers' sites, the fleet-related costs of trucks, and exploitation
costs of FLD fleet. Constraints (2) and (3) ensure that each customer is served once or
more by trucks. Constraints (4) and (5) assure that each route of trucks is composed of a
maximum one truck. Constraints (6) guarantee a flow conservation. Constraints (7) relate
to sub-tour elimination constraints. See Desrochers et al. (1988) for more details.
Constraint set (8) guarantees the feasibility of the working time of trucks. Constraints (9)
and (10) describe that the import/export loaded containers are directly carried between the
inland depot and customers' sites. Constraint set (11) defines that the empty container
demand is the difference between the number of import and export containers of the
customer. Constraints (12) and (13) specify the transportation capacity of trucks for loaded
and empty containers, respectively. The number "4" in the constraints (13) means that up
to four FLDs can be folded and bundled into one package. Four folded and bundled FLDs
are equal to the capacity of a single STD. Constraint set (14) guarantees that loaded and
empty containers cannot be moved by the same truck at the same time. Eqs. (15) and (16)
define the absolute number of loaded and empty containers that are loaded or unloaded
to/from trucks at each site, respectively. Constraints (17)–(19) specify the substantive
number of F/UF containers that are loaded or unloaded to/from trucks at each site
incorporating the use by indicator variables. Those constraints mean that up to four folded
and bundled FLDs can be loaded or unloaded to/from trucks as a single STD. Likewise,
Eqs. (20) define the absolute number of FLDs that are folded/unfolded at each site.

Constraints (21)–(26) determine the number of empty containers which is moved alone
without being folded between customers' sites. Namely, those constraints are counting the
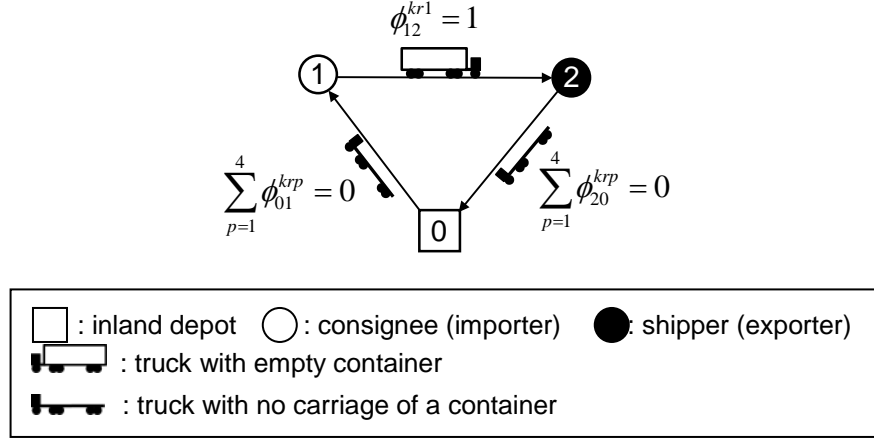
Fig. 2 An example of a single FLD moving without folding/unfolding

number of unfolded (erected) containers which are distributed as a single STD between
customers' sites, because the F/UF process is unnecessary when a single FLD is directly
exchanged between customers. Fig. 2 demonstrates an example of a single FLD
movement without F/UF process between customers' sites. In this situation, if η_{12}^{kr} in
constraint (23) has accordingly the specific value (=3), then $\lambda_{12}^{kr3} = 1$ and $US_{12}^{kr} = 1$. Eq. (27)
specifies that the sum of import shipments corresponds with the total containers in the
hinterland. Eqs. (28)–(30) define the truck fleet size.

3.3.2 Formulation for DX with STDs

The model for this scenario is built as follows:

[DX_STD]

Minimize $\displaystyle\sum_{k \in K}\sum_{r \in R}\sum_{i \in N}\sum_{j \in N} C_{ij}^{T} X_{ij}^{kr} + C^{H}\sum_{k \in K}\sum_{r \in R}\sum_{i \in N}\left(2FH_{i}^{kr} + EH_{i}^{kr}\right) + C^{V} \cdot V + C^{FS} \cdot FS$ (39)

subject to

(2)–(12), (15), (16), (28)–(30), (32), (35), (36)

$EZ_{ij}^{kr} \le X_{ij}^{kr} \quad \forall i, j \in N, k \in K, r \in R,$ (40)

$EZ_{ij}^{kr} + FZ_{ij}^{kr} \le 1 \quad \forall i \in N, j \in Q_{i}, k \in K, r \in R,$ (41)

$FS = \displaystyle\sum_{i \in N} D_{i},$ (42)

$FS, V \ge 0 \quad \text{and integer},$ (43)

$EZ_{ij}^{kr}, FZ_{ij}^{kr} \ge 0 \quad \text{and integer} \quad \forall i, j \in N, k \in K, r \in R,$ (44)

$$EH_i^{kr}, FH_i^{kr} \geq 0 \quad \text{and integer} \quad \forall i \in N, k \in K, r \in R. \tag{45}$$

where

FS container fleet size of STDs

C^{FS} exploitation cost of STD.

The objective function (39) minimizes the total costs, which consist of: the costs of
the movements of containers by trucks, the costs of loading and unloading containers
to/from trucks, the fleet-related costs of trucks, and the exploitation costs of STD fleet.
Constraint set (40) specifies the transportation capacity of trucks for empty containers.
Constraints (41) guarantee that loaded and empty containers cannot be moved by the same
truck at the same time. Each truck can move a single STD once. Eq. (42) specifies that the
sum of import shipments corresponds with the total containers in the hinterland.

3.3.3 Formulation for IX with FLDs
The model for this scenario is constructed as follows:

[IX_FLD]

Minimize
$$\sum_{k \in K} \sum_{r \in R} \sum_{i \in N} \sum_{j \in N} C_{ij}^T X_{ij}^{kr} + C^H \sum_{k \in K} \sum_{r \in R} \sum_{i \in N} \left(2FH_i^{kr} + UH_i^{kr}\right) + C^U \sum_{k \in K} \sum_{r \in R} \sum_{i \in N/\{0\}} U_i^{kr}$$
$$+ C^V \cdot V + C^{FF} \cdot FF \tag{46}$$

subject to

(2)–(10), (12)–(15), (17)–(20), (27)–(33), (35), (36)

$$\sum_{k \in K} \sum_{r \in R} EZ_{i0}^{kr} - \sum_{k \in K} \sum_{r \in R} EZ_{0i}^{kr} = D_i - P_i \quad \forall i \in N \setminus \{0\}, \tag{47}$$

$$-EH_i^{kr} \leq \sum_{j \in Q_i} EZ_{ij}^{kr} - \sum_{h \in Q_i} EZ_{hi}^{kr} \leq EH_i^{kr} \quad \forall i \in N, k \in K, r \in R, \tag{48}$$

$$EZ_{ij}^{kr}, FZ_{ij}^{kr}, US_{ij}^{kr} \geq 0 \quad \text{and integer} \quad \forall i, j \in N, k \in K, r \in R, \tag{49}$$

$$\delta_{ij}^{krp} \in \{0,1\} \quad \forall i, j \in N, k \in K, r \in R, p \in \{1,...,4\}. \tag{50}$$

The objective function (46) is partially changed in terms of the costs of F/UF
containers from the objective function (1), since a single empty FLD is not exchanged
between customers' sites. Constraints (47) define that the empty container demand is the
difference between the number of import and export containers, and this constraint only
allows empty containers to be exchanged between the inland depot and customers.
Inequalities (48) determine the absolute number of empty containers that are loaded or
unloaded to/from trucks at each site, because empty containers cannot be directly
exchanged between customers' sites.

3.3.4 Formulation for IX with STDs

The model for this scenario is formulated as follows:

[IX_STD]

Minimize   (39)

subject to

(2)–(10), (47), (12), (40), (41), (15), (48), (42), (28)–(30), (43), (32), (44), (45), (35), (36).

4. SOLUTION PROCEDURE

This section describes a solution procedure for the CRVRP, which seeks to service a number of customers with a truck fleet and to satisfy transportation demand such as loaded and empty container transportation requests between the inland depot, consignees and shippers.

4.1 Heuristics

Similar to the most VRP, the CRVRP is NP-hard. A lot of NP-hard problems are solved optimally by some exact methods such as a branch-and-bound procedure, however this solving process would be time-consuming, especially for problems of practical size, which involve a lot of customers' sites to be visited. Since a trucking firm may wish to solve the CRVRP quickly, because of frequent delivery information updates, fast computation is needed. This encourages us to apply a meta-heuristic for solving the problem. From this point of view, this paper proposes an SA-based meta-heuristic to find a nearly optimal solution.

SA algorithm was originally inspired from the process of annealing in metal work. Annealing involves heating and cooling a material to alter its physical properties due to the changes in its internal structure. As the metal cools its new structure becomes fixed, consequently causing the metal to retain its newly obtained properties. In SA, we keep a temperature variable to simulate this heating process. We initially set it high and then allow it to slowly "cool" as the algorithm runs. While this temperature variable is high, the algorithm is allowed, with more frequency, to accept solutions that are worse than the current solution. This process gives the ability to jump out of any local optimal solutions it finds itself in the early stage of execution. As the temperature is lowered, the chance of accepting worse solutions become smaller. Therefore, allowing the algorithm to gradually focus on an area of the search space, a close to optimal solution can be found. This gradual "cooling" process is what makes SA algorithm effective at finding a close to optimal solution when dealing with large problems which contain numerous local optimal solutions.

Since SA has been successfully applied to a large number of combinatorial

optimization problems, it is not described here in detail. See Kirkpatrick et al. (1983) and
Cerny (1985) for more details.

4.2 Basic elements of SA

The implementation of SA algorithm is remarkably easy. The pseudocode for SA is
presented as Algorithms 1 and 2. The basic elements of SA are following:

  – A representation of feasible solutions,
  – A generator of random changes in the solutions,
  – A means of evaluating the problem functions, and
  – An annealing schedule - an initial temperature and rules for lowering it as the
  search progresses.

SA improves the strategy through the introduction of two parts. The first part is the so-
called "Metropolis algorithm" (Algorithm 2), in which some trades that do not lower costs
are accepted when they serve to allow the solver to "explore" more of the possible space
of solutions. Such "not good" trades are allowed using the criterion
that $Rand < \exp(-\Delta Cost / T)$, where $\Delta Cost$ is the difference in cost between old and
neighboring solutions implied by the trade (negative for a "good" trade; positive for a "not
good" trade), T is a "synthetic temperature", and $Rand$ is a random number in the
interval $[0,1)$. $Cost(\cdot)$ is a "cost function". If T is high, many "not good" trades are
accepted, and a large part of solution space is accessed. Objects to be traded are generally
chosen randomly, though more sophisticated techniques can be used.

The second part is to lower the "temperature." After making many trades and
observing that the cost function declines only slowly, one lowers the temperature, and thus
limits the size of allowed "not good" trades. After lowering the temperature several times
to a low value, one may then "quench" the process by accepting only "good" trades in
order to find the local minimum solution of the cost function. There are various "annealing
schedules" for lowering the temperature, however the results are generally not very
sensitive to the details.

Algorithm 1. Simulated annealing algorithm

Algorithm *Simulated_annealing* (T, M, α, β);

begin
    Initialize $T = $ initial temperature, $M = $ number of parameters updated,
        $\alpha = $ cooling rate, $\beta = $ constant;
    Generate initial solution, S_0;
    Current solution, $Cur\_S = S_0$;
    Best solution, $Best\_S = Cur\_S$;
    $Time = 0$;
        repeat

$CurCost = Cost(Cur\_S)$;

$BestCost = Cost(Best\_S)$;

   Call $Metropolis(Cur\_S, CurCost, Best\_S, BestCost, T, M)$;

$Time = Time + M$;

$T = \alpha T$;

$M = \beta M$;

until $Time \geq$ Total processing time;

end.

Algorithm 2. Metropolis algorithm

Algorithm $Metropolis(Cur\_S, CurCost, Best\_S, BestCost, T, M)$;

begin

   $Iter = 1$;

   repeat

   Generate neighborhood solution, $New\_S = Neighbor(Cur\_S)$;

   $NewCost = Cost(New\_S)$;

   $\Delta Cost = NewCost - CurCost$;

      if $\Delta Cost < 0$ **then**

         $Cur\_S = New\_S$;

         if $NewCost < BestCost$ **then**

            $Best\_S = New\_S$;

         endif

      else

         Generate random number [0,1), $Rand$;

         if $Rand < \exp(-\Delta Cost / T)$ **then**

            $Cur\_S = New\_S$;

         endif

      endif

   $Iter = Iter + 1$;

   until $Iter \geq M$;

end.

4.3 Virtual truck route with dummy nodes

   The SA requires designing the solution structure for solving the problem. Since the CRVRP deals with the integratation of both truck routing and empty container relocation, we assume the virtual truck route to be associated with some kinds of dummy nodes, in order to explicitly distinguish the shipment status of trucks, i.e., loaded container, empty container or no carriage,. The sets of dummy nodes are, namely: for consignee dummy

nodes (N^D: delivery point D of loaded (imported) container, N^{Es}: supply point Es of empty container), for shipper dummy nodes (N^P: pickup point P of loaded (exporting) container, N^{Ed}: demand point Ed of empty container), and for the inland dummy nodes ($N^{Es'}$: supply point Es' of empty container, $N^{Ed'}$: demand point Ed' of

(a) DX   (b) IX

□ : inland depot   ○ : consignee (importer)   ● : shipper (exporter)
⬭ : dummy node
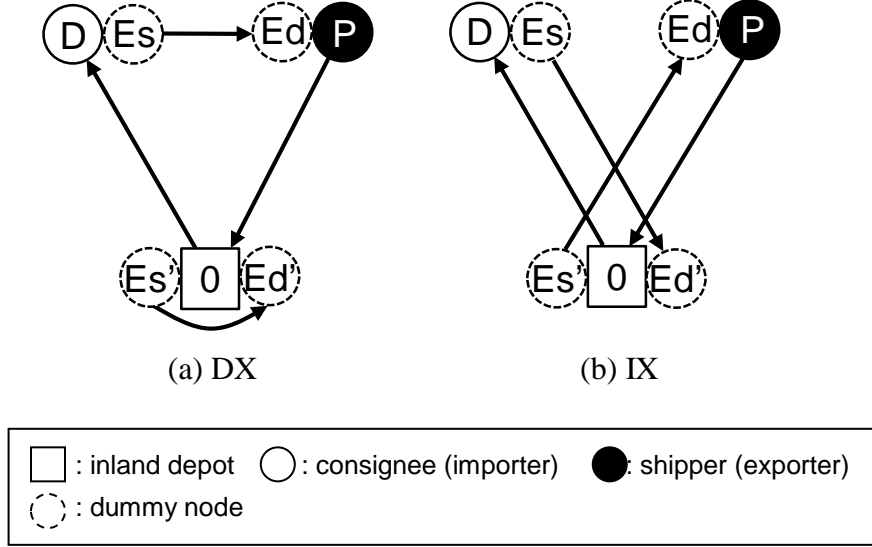
Fig. 3 An example of the virtual truck routes with dummy nodes in case of using STDs

empty container). We assume $\left|N^D\right|=\left|N^{Es}\right|=\left|N^{Ed'}\right|$ and $\left|N^P\right|=\left|N^{Ed}\right|=\left|N^{Es'}\right|$ where $\left|N^D\right|$ is the cardinality of N^D. Note that the SDVRP described in Subsection 3.1 can reduce the problem to the VRP with equal demand by employing the dummy nodes.

Fig. 3 shows an example of relocation scenarios of empty containers DX and IX with dummy nodes in case of using STDs. At the delivery point D, once the imported container from the inland depot "0" becomes empty, it is automatically transferred to the supply point Es, and the empty container is ready to be repositioned from Es to Ed (DX) or Ed' (IX). Furthermore, after the empty container is repositioned from Es (DX) or Es' (IX) to Ed, then the empty container is automatically transferred to P.
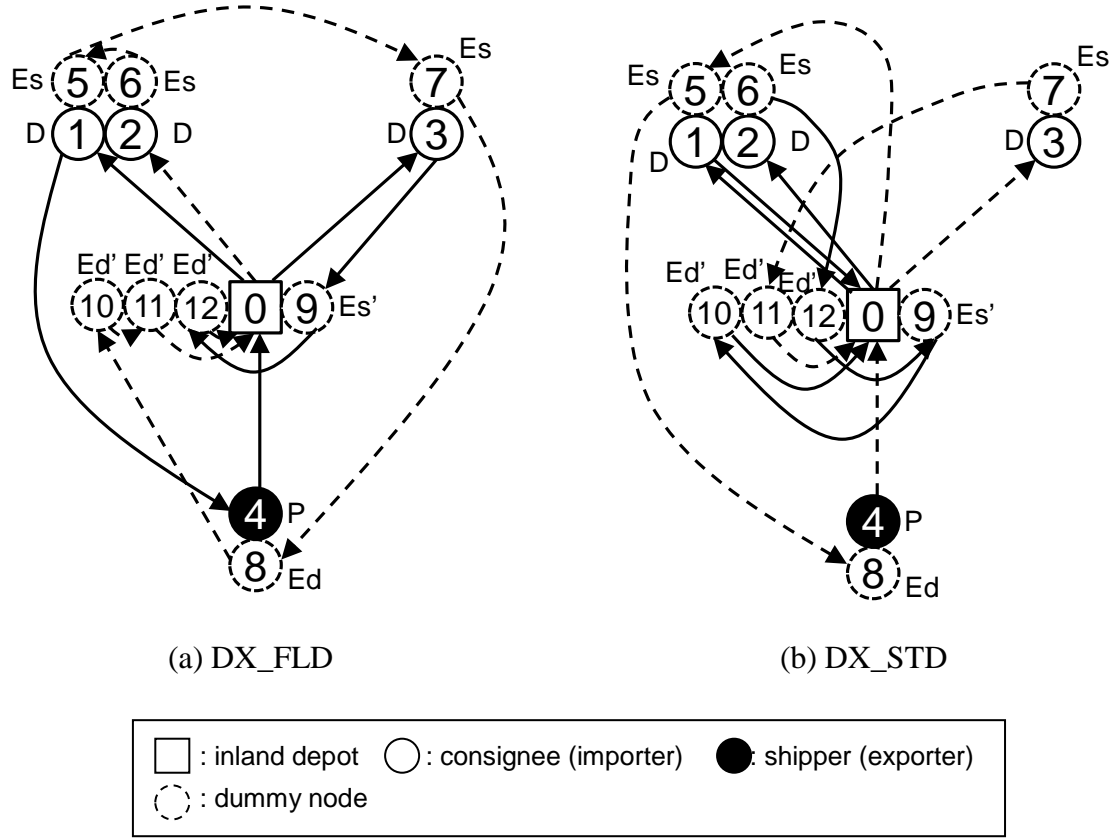
An exporting cargo is stuffed into the empty at P, and that laden container is transported from P to the inland depot "0". In the scenario IX, empty containers are moved through $Es \rightarrow Ed'$ or $Es' \rightarrow Ed$, because trucks are only allowed the indirect exchange of empty containers via the inland depot.

Note that, in case of using FLDs, since each truck has a transportation capacity of four empty FLDs, trucks can serve the scenarios DX and IX within the capacity between Es, Es', Ed and Ed'. Constraints (13) and (40) guarantee the capacities for FLDs and STDs, respectively.

4.4 Solution generation

According to Fig. 1a and b, Fig. 4 illustrates an example of truck movements and loaded/empty containers transportations for DX_FLD and DX_STD, respectively. In case

of DX_FLD, loaded (import/export) containers are transported through the node pair $0 \rightarrow D$ or $P \rightarrow 0$, then empty containers can possibly be carried between Es, Es', Ed and Ed', because trucks can freely serve between customers within the capacity. Surely, as mentioned in the previous subsection, trucks run with no cost in the arc (node pair),

(a) DX_FLD   (b) DX_STD

☐ : inland depot   ◯ : consignee (importer)   ● : shipper (exporter)
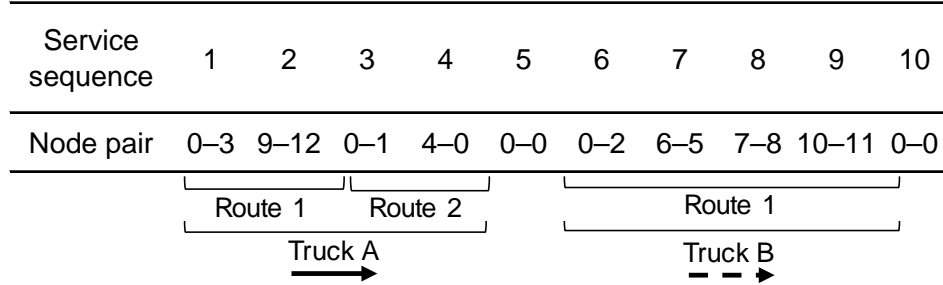⬭ : dummy node

Fig. 4 An example of service routes for SA

which consists of the originally identical node.

Fig. 5 shows an example of feasible solutions corresponding to Fig. 4, in case of DX_FLD, Truck A serves 0–3–9–12–0–1–4–0, and Truck B serves 0–2–6–5–7–8–10–11–0. On the other hand, in case of DX_STD, Truck A serves 0–2–6–12–9–10–0–1–0, and Truck B serves 0–5–8–4–0–3–7–11–0. If a truck working time reaches the limit, then the artificial node pair "0–0", which means the end of the service route by the specific truck, is inserted to the previous node pair to obtain a feasible solution. To distinguish the end of the service route by either the specific truck or the identical truck, we employ that representation, namely, the artificial node pair "0–0".
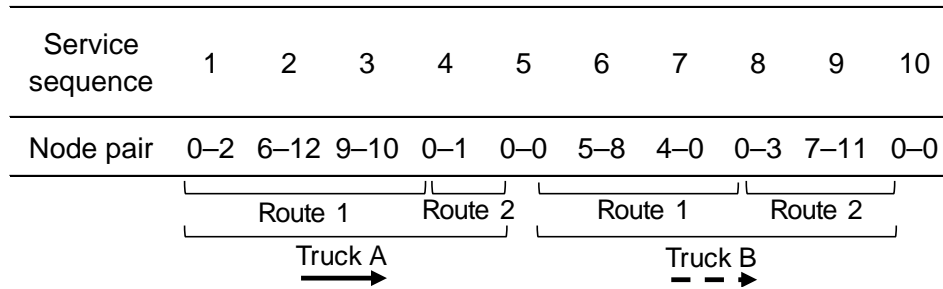
To generate a neighborhood solution, randomly choose two node pairs from the current solution, and then exchange them. In cases of DX_FLD and IX_FLD, additionally, it is effective to swap two nodes which are contents of a node pair.

5. COMPUTATIONAL EXPERIMENTS

The SA is coded in Fortran77 and is run on a DELL Precision T7910 with Intel Xeon 2.4 GHz, RAM 32 GB. Problems used in the experiments are generated randomly, however systematically controlled for customer locations and transportation requests of customers.

Service sequence	1	2	3	4	5	6	7	8	9	10
Node pair	0–3	9–12	0–1	4–0	0–0	0–2	6–5	7–8	10–11	0–0

Route 1 — Route 2 (Truck A) → Route 1 (Truck B) ---▶

(a) DX_FLD

Service sequence	1	2	3	4	5	6	7	8	9	10
Node pair	0–2	6–12	9–10	0–1	0–0	5–8	4–0	0–3	7–11	0–0

Route 1 — Route 2 (Truck A) → Route 1 — Route 2 (Truck B) ---▶

(b) IX_FLD

Fig. 5 Feasible solutions
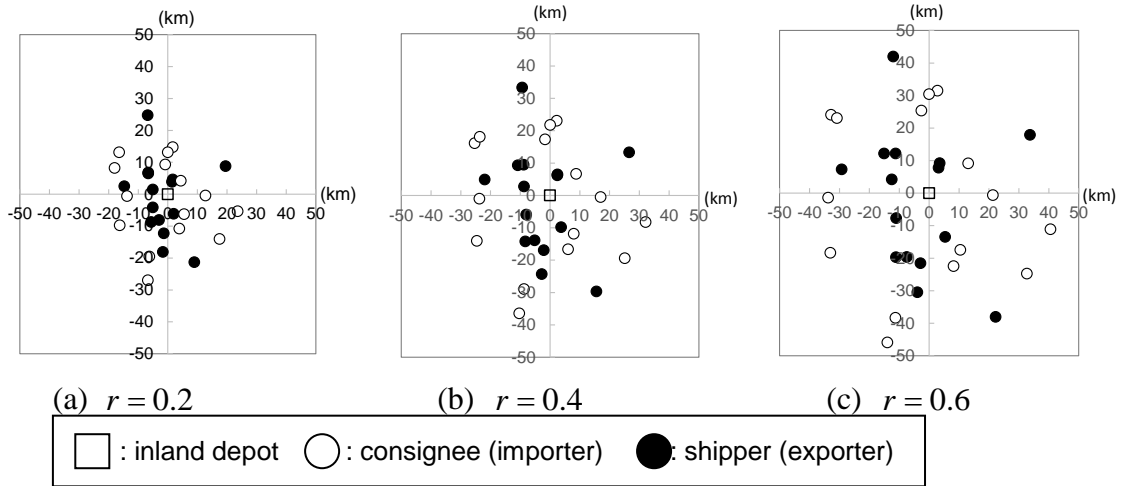
5.1 Experimental design

We provide six basic problem scenarios, three of which have the number of throughput containers (NC) (daily total of import and export containers) in the hinterland varying as 30, 60 and 90 FEUs (FEU, Forty-foot Equivalent Unit). Since we assume three levels of NC, there are successively 90, 180 and 270 nodes to form the virtual truck routes from dummy nodes. The other three problems consider different levels of the imbalance ratio (IR) in cargo flow, approximately, 1:1, 2:1 and 3:1, between import and export containers. Note, however, that the assumed total traffic of containers in the hinterland remains constant for each imbalance ratio.

Additionally, the problem scenarios are expected to be more valuable with more widespread demand location from the inland depot to customers, because $D-P$ pairs with a longer hauling distance result in inefficient use of the truck working time. Following Imai et al. (2007), the coordinates (x_i, y_i) of the location of customer i are defined as

$$(x_i, y_i) = (R1_i \times 100 - 50) \times (r + R2_i \times 0.4),$$

where r is a parameter of 0.2, 0.4 or 0.6, and $R1_i$ and $R2_i$ are two series of random numbers in the interval [0,1]. By varying r, we can determine the distance ranges of

customer locations from the inland depot as shown in Fig. 6. Additionally, we take account of the other problems regarding the lot size of containers (LS) that customers handle, to observe whether FLDs can be candidate empty containers which can be bundled together as a single container. LS is defined as follows:

(a) $r = 0.2$ (b) $r = 0.4$ (c) $r = 0.6$

□ : inland depot   ○ : consignee (importer)   ● : shipper (exporter)

Fig. 6 Customers' locations with varied distance ranges

Table 1 Experimental design

Factor	Level description
NC	30, 60, 90 (FEUs)
LS	S– 1, M– 2, L– 4
IR	B– 1:1, D– 2:1, T– 3:1
r	N– 0.2, M– 0.4, W– 0.6

$$\text{the lot size of containers}\,(\text{LS}) = \text{the number of containers customers handle}/$$
$$\text{the number of customers}.$$

If LS has a real value, it is adjusted to be an integer value. We assume three different levels of LS as 1, 2 and 4.

The experimental design with the factors is shown in **Table 1**.

5.2 Parameter settings

Data on drayage costs by trucks were derived from rates obtained from some trucking companies and a public source, while the rate for handling containers at the inland terminal was assumed based on literature information and checked by an inland terminal operator. The F/UF cost of an FLD was provided by an FLD manufacturer. Our interviews with companies that have developed FLDs learned that the costs for folding are about the same as the costs for unfolding. Therefore our assumption to give these processes the same parameter value in our model is justified. The exploitation cost of an FLD is assumed to be twice as high as for an STD, taking into account the estimated additional purchase,

maintenance and repair costs of the FLD. Based on these sources the following parameter
settings were used for the numerical experiments:

(i) Total (daily) cargo flow: 30, 60 and 90 FEUs

(ii) The imbalance ratio between import and export cargo flows to the hinterland region:
1:1, 2:1, and 3:1

(iii)Number of customers: the number is depending on the combination of NC, IR and LS.

(iv)Distance range between the inland depot and customers: 0 to 70 km (the range is
depending on the parameter r)

(v) Transportation cost, C_{ij}^T is defined as $C_{ij}^T = 1.45 *$ distance €/FEU (the   distance   is
depending on node pairs)

(vi)Truck fleet cost, $C^V = 105$ €/truck/day

(vii) Handling cost, $C^H = 40$ €/FEU

(viii) F/UF cost, $C^U = 40$ €/FEU/process

(ix)Exploitation cost, $C^{FF} = 2$ €/FEU/day for an FLD, and $C^{FS} = 1$ €/FEU/day for an STD

Note that once a specific combination of NC, IR and LS is given, the number of
customers (importers/exporters) (iii) is automatically determined. For parameters (v)–(ix)
data are obtained from Shintani et al. (2010). In this study, the relocation cost by truck is
associated with variable and fixed costs. We assume that the former is the transportation
cost (v) and the latter is the truck fleet cost (vi). Note that an imbalance ratio 1:1 in (ii)
assumes balanced flows at an aggregate level, but it may still involve a need of container
reposition in the hinterland because export and import volumes of the individual
customers are likely to be imbalanced.

Based on preliminary experiments, parameters of the SA were set as follows: *Time*
$= 100,000$, $T = 50,000$, $\alpha = 0.9$, $\beta = 1.1$ and $M = 10$.
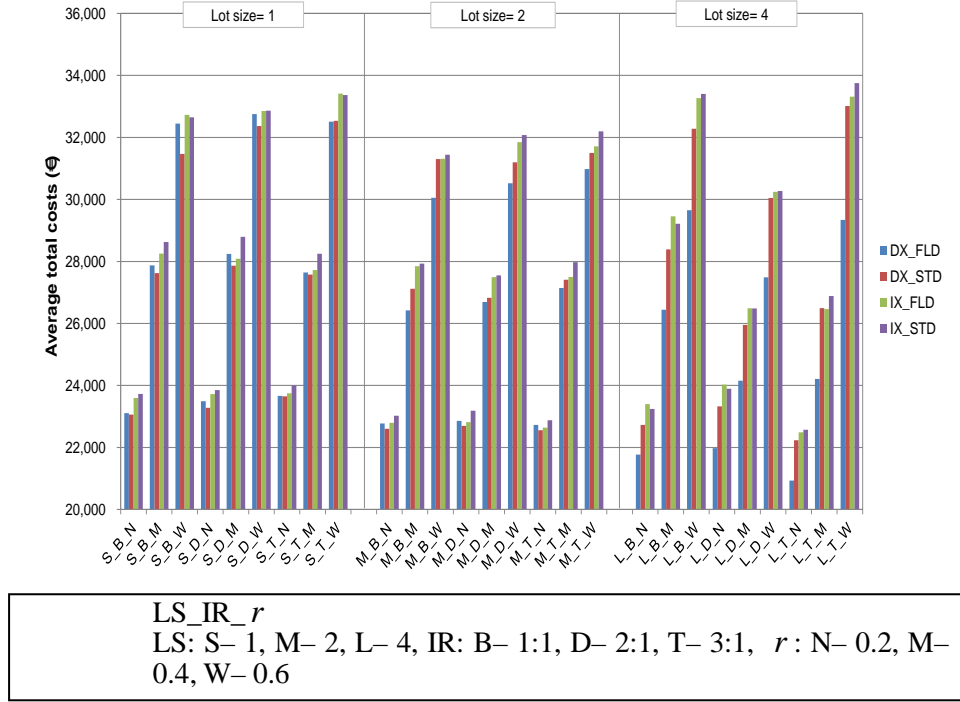
5.3 Experimental results

Based on 81 problem samples with a combination of NC, IR, LS and r, where each
factor has three levels of values, computational results of four models (i.e. DX_FLD,
DX_STD, IX_FLD and IX_STD) are reported in Figs. 7–11. For each problem sample,
50 variations are generated by placing pickup and delivery points and demand quantities
for loaded containers randomly with different seed sets of random numbers. So, the "total
costs" of a problem sample in those figures is reported as average over the 50 variations.

For practical reasons, hereafter, we will only present the results regarding the case
NC=90 FEUs. For the cases NC=30 and 60 FEUs we only illustrate the results on the total
costs as shown in Appendix A, because the results of those cases denote the same patterns
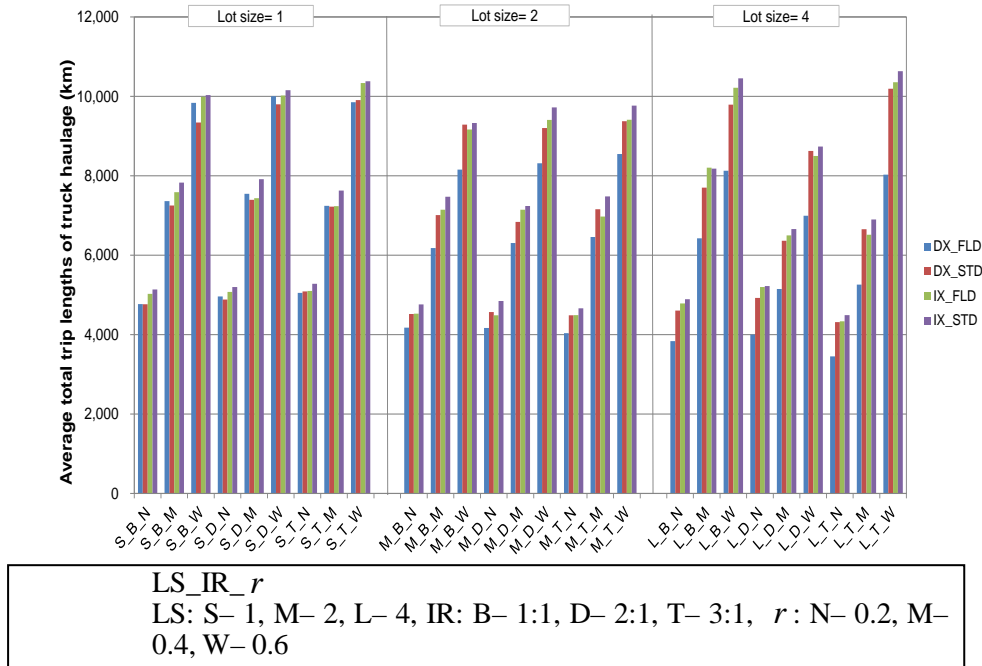as the results in the case NC=90 FEUs.

We first look at the difference in the total costs obtained from four models varying IR,
LS and r as mentioned in Subsection 5.2. In Fig. 7 the cost performances of four models
are presented. One can see at a glance that DX_FLD remarkably offers the lowest total

costs especially when LS and r increase. Moreover, DX tends to provide lower total costs than IX even for the same container type.

Fig. 8 demonstrates the trip lengths of truck haulage in various cases. DX_FLD significantly provides the shorter trip length than the other models in which LS and r are larger.


LS_IR_r
LS: S– 1, M– 2, L– 4, IR: B– 1:1, D– 2:1, T– 3:1, r : N– 0.2, M–
0.4, W– 0.6

Fig. 7 Average total costs in various cases (NC=90 FEUs)

LS_IR_r
LS: S– 1, M– 2, L– 4, IR: B– 1:1, D– 2:1, T– 3:1, r : N– 0.2, M–
0.4, W– 0.6

Fig. 8 Average total trip lengths of truck haulage in various cases
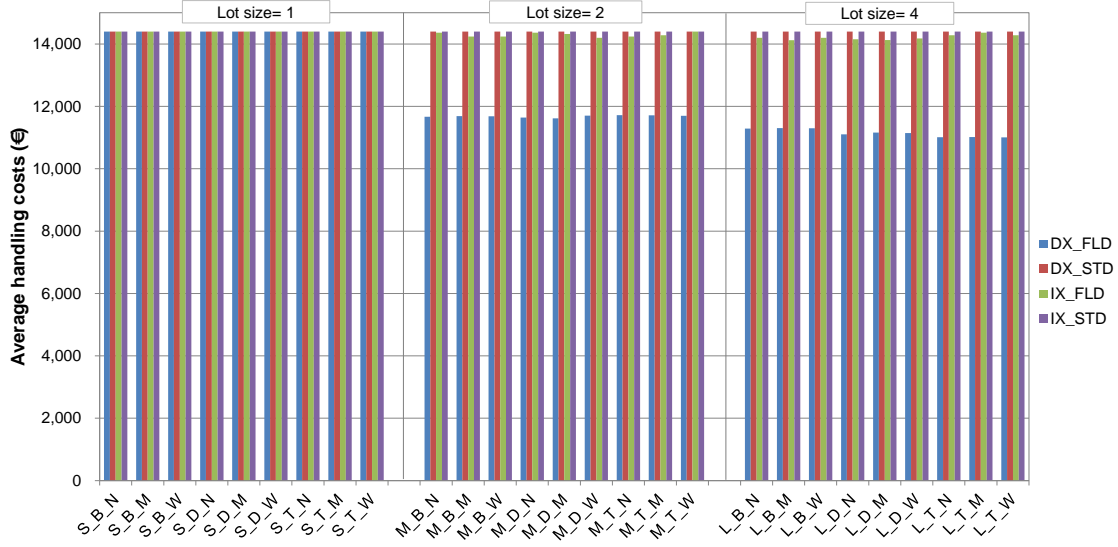(NC=90 FEUs)

Fig. 9 shows the breakdown of the trip lengths in the imbalance ratio 3:1, focusing on the shipment status of trucks, i.e. loaded container, empty container and no carriage. As LS is getting large, DX_FLD reduces the trip length of both empty container relocation and no carriage, and can improve the efficiency of using trucks.
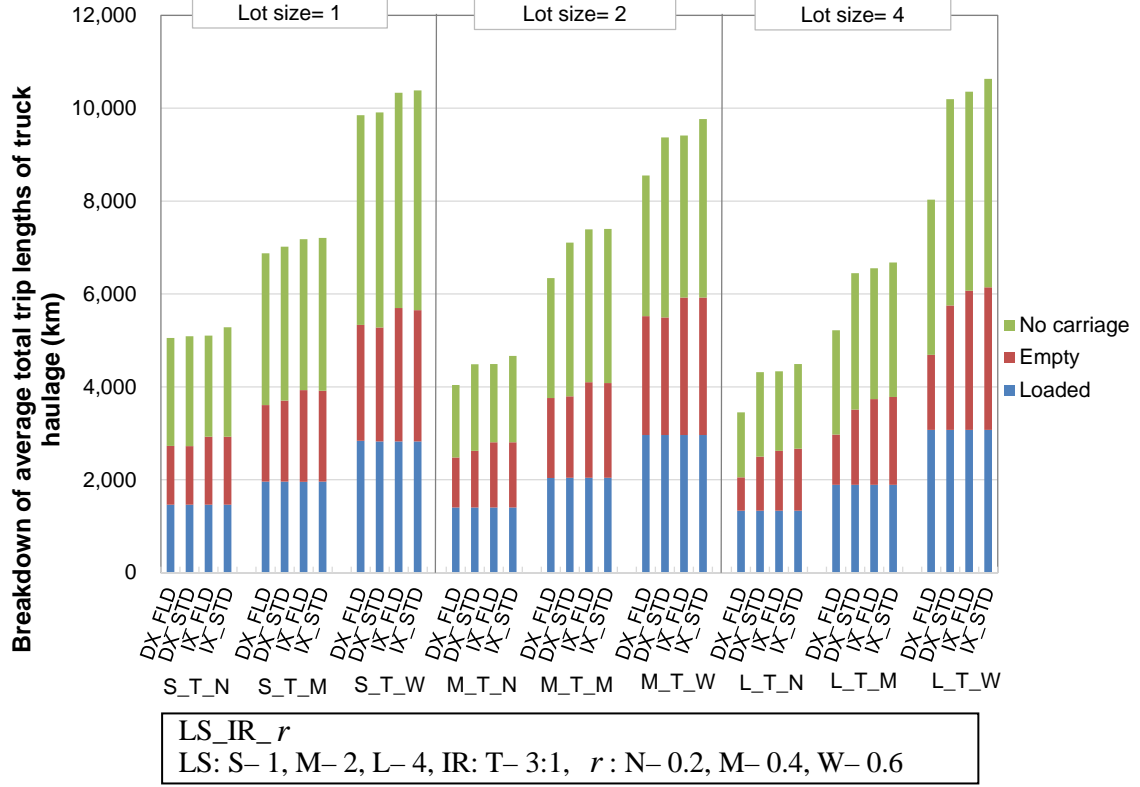
Fig. 9 Breakdown of average total trip lengths of truck haulage in various cases
(NC=90 FEUs)
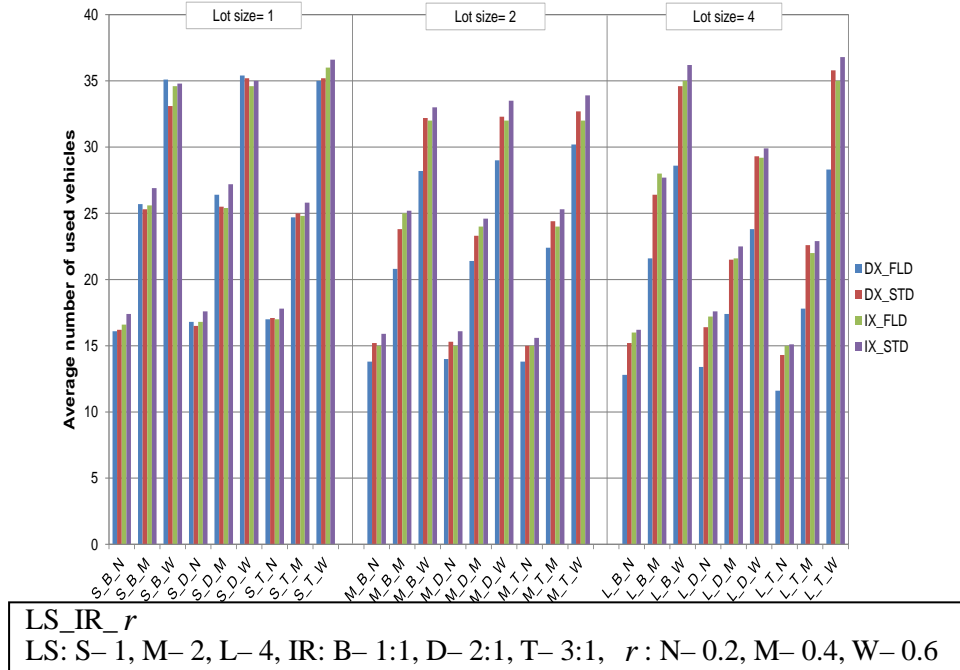
Fig. 10 Average number of used trucks in various cases (NC=90 FEUs)

Fig. 11 Average handling costs in various cases (NC=90 FEUs)

Fig. 10 illustrates the total number of used trucks in various cases. DX_FLD leads to the smallest number of trucks to use especially at increasing values of LS and *r* compared to the other models. Therefore it means that DX_FLD can improve the efficient use of trucks.

Fig. 11 shows the handling costs in various cases. If LS is getting large, DX_FLD provides the lowest handling costs. There are significant reductions in the gap value for the cases LS=2 and 4 that offer 14% and 20% cost reductions respectively, compared to the case LS=1. The obvious reason is that a large LS enables FLDs to be folded and bundled; a bundle of FLDs reduces the number of handling. Up to four folded FLDs can be handled as a single STD in one time. Note that IX_FLD has a small effect on F/UF costs, due to the individual handling of FLDs at each customer.

6. CONCLUSIONS

This study addressed the issue of empty container relocation by trucks in the hinterland transportation of a seaport. Although much has been written on empty container relocation, very few studies have appeared on foldable containers, and none with the ability to deal with the integrated problem of both truck routing and empty container relocation by using foldable containers. To fill this gap, IP models were developed in this article with the ultimate aim of showing the possibilities to realize cost savings by using foldable containers. We modeled the CRVRP to minimize the total costs. The SA algorithm-based meta-heuristic was developed for solving the problem.

From computational experiments, the conclusion can be drawn that FLDs can significantly reduce the number of used trucks, trip length of truck haulage and the number of handlings compared to STDs, resulting in substantial cost savings. These savings are especially apparent in situations of a direct exchange of empty containers between

customers and a large distance between the inland depot and customers' sites, and a large lot size of containers to be handled by individual customers. A sensitivity analysis on the exploitation costs of foldable containers and cost of folding/unfolding could make the business case for foldable containers stronger, in which the cost estimations used in this study have been confirmed as reasonable by container designers and manufacturers.

This article surely raises awareness on the possibilities for viable commercial operations of foldable containers. However, the specific characteristics of the transportation chain, as we have shown here, remain paramount to achieve real benefits in using foldable containers.

ACKNOWLEDGEMENT

APPENDIX Average total costs in various cases (NC=30 and 60 FEUs).

Table A.2 Average total costs in various cases (NC=30 FEUs)　　(€)

LS_IR_ *r*	DX_FLD	DX_STD	IX_FLD	IX_STD
S_B_N	**7,302.6**	7,405.7	7,648.7	7,560.5
S_B_M	**8,630.7**	8,746.4	9,091.2	8,996.6
S_B_W	**9,993.7**	10,192.5	10,650.1	10,574.3
S_D_N	**7,378.5**	7,414.5	7,619.2	7,574.1
S_D_M	**8,729.1**	8,832.7	9,125.0	9,029.6
S_D_W	**9,778.9**	9,956.6	10,234.9	10,195.5
S_T_N	**7,369.0**	7,449.5	7,643.2	7,590.9
S_T_M	**8,734.4**	8,893.5	9,063.4	9,042.3
S_T_W	**9,955.6**	10,159.6	10,437.9	10,412.8
M_B_N	**7,192.3**	7,258.6	7,434.5	7,390.0
M_B_M	8,989.2	**8,923.9**	9,220.5	9,198.5
M_B_W	**9,632.9**	9,750.5	10,191.7	10,188.7
M_D_N	**6,941.1**	7,327.1	7,457.2	7,430.2
M_D_M	**8,038.1**	8,457.3	8,664.4	8,725.7
M_D_W	**8,911.3**	9,435.3	9,693.4	9,656.7
M_T_N	**7,196.1**	7,413.8	7,459.4	7,458.7
M_T_M	**7,976.1**	8,532.6	8,722.2	8,724.6
M_T_W	**9,062.1**	9,679.8	9,754.8	9,897.4
L_B_N	**7,399.2**	7,952.5	8,167.7	8,257.7
L_B_M	**8,770.1**	9,749.7	9,697.5	9,952.1
L_B_W	**9,432.4**	10,348.1	10,426.6	10,641.6
L_D_N	**6,936.4**	7,472.1	7,424.8	7,518.8
L_D_M	**7,865.8**	8,376.0	8,445.2	8,547.0
L_D_W	**7,921.8**	8,570.2	8,707.4	8,859.5
L_T_N	**7,334.2**	7,875.5	7,926.3	7,973.1
L_T_M	**7,939.3**	8,629.2	8,545.5	8,640.6
L_T_W	**8,718.0**	9,501.8	9,293.3	9,522.9

Boldface denotes the best solutions.

LS　S– 1, M– 2, L– 4

IR　B– 1:1, D– 2:1, T– 3:1

r　N– 0.2, M– 0.4, W– 0.6

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Table A.3 Average total costs in various cases (NC=60 FEUs)　　(€)

LS_IR_ *r*	DX_FLD	DX_STD	IX_FLD	IX_STD
S_B_N	**14,996.2**	15,053.9	15,900.4	15,430.2
S_B_M	18,169.7	**18,053.0**	18,570.8	18,680.5
S_B_W	**20,707.1**	20,728.9	21,248.9	21,487.8
S_D_N	15,208.7	**15,132.9**	15,409.8	15,478.1
S_D_M	18,051.0	**17,896.7**	18,689.1	18,420.9
S_D_W	21,083.5	**20,826.2**	21,441.4	21,500.5
S_T_N	15,622.9	15,610.7	**15,527.7**	15,885.7
S_T_M	18,070.5	**18,038.8**	18,605.1	18,425.5
S_T_W	21,423.7	**21,328.9**	21,796.4	22,015.0
M_B_N	15,129.6	**14,945.1**	15,145.1	15,240.6
M_B_M	**17,640.0**	17,817.0	18,758.2	18,279.3
M_B_W	**20,484.2**	20,775.0	20,949.0	21,625.7
M_D_N	**14,773.0**	15,031.9	15,304.5	15,324.6
M_D_M	**17,304.5**	17,809.7	18,535.3	18,288.1
M_D_W	**19,247.6**	20,197.4	20,748.7	20,701.0
M_T_N	**14,896.1**	15,384.6	15,723.0	15,618.7
M_T_M	**16,972.9**	17,952.4	18,409.5	18,329.6
M_T_W	**19,724.8**	21,138.6	21,692.4	21,669.2
L_B_N	**14,091.5**	14,776.2	15,170.9	15,124.0
L_B_M	**17,214.1**	18,374.1	18,760.8	18,883.4
L_B_W	**18,409.1**	19,911.7	20,782.9	20,789.0
L_D_N	**13,977.4**	14,781.0	15,052.7	15,028.5
L_D_M	**15,757.7**	16,925.3	17,331.0	17,331.4
L_D_W	**18,596.9**	20,330.1	20,726.3	20,874.0
L_T_N	**14,621.1**	15,471.4	15,646.6	15,612.5
L_T_M	**15,380.7**	16,491.2	16,775.1	16,746.6
L_T_W	**18,188.0**	19,817.2	20,155.6	20,304.0

Boldface denotes the best solutions.

LS　S– 1, M– 2, L– 4

IR　B– 1:1, D– 2:1, T– 3:1

r　N– 0.2, M– 0.4, W– 0.6

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