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INTEGRATING EMPTY CONTAINER ALLOCATION WITH VEHICLE ROUTING IN INTERMODAL TRANSPORT

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ABSTRACT

In an intermodal transportation network, empty containers need to be repositioned in order to be able to fulfil empty container demands. At a regional level this repositioning takes place between importers, exporters, intermodal terminals, inland depots and ports. Repositioning movements with lowest costs may be determined by an empty container allocation model. Vehicle routing models may be used to find vehicle routes for performing loaded containers transports and container allocations determined by the container allocation model. Recently, approaches to integrate empty container allocations and vehicle routing have been discussed in literature. This paper shows the advantage of an integrated approach for the full-truckload problem with a vehicle capacity of a single container. Mathematical formulations for the container allocation and vehicle routing model are proposed. A model integrating the separate models is presented and numerical experiments are performed. Results show that the integrated model results in the lowest costs.

Keywords: empty container allocation, vehicle routing, pre- and post-haulage, intermodal freight transport

1. INTRODUCTION

Ever since the introduction of containers, containerization of freight transport, especially in international maritime shipping, is rising. The use of containers for freight transportation leads to a number of planning problems, such as fleet sizing and management, decisions about container ownership or leasing and repositioning needs (Dejax and Crainic 1987). This paper considers the last aspect, repositioning needs, in an intermodal transportation network consisting of maritime main haulage and pre- and post-haulage over land by truck, rail or barge transport.

Due to the natural imbalance of trade, certain areas in the network develop a surplus of containers while others have a deficit. As a consequence, there is a need for carriers to reposition their empty containers in order to be able to fulfil future demand for empty containers. Although it is a costly and non-revenue generating

activity, empty container repositioning is an integral part of an overall efficient transportation system. In an intermodal transportation network, empty container repositioning takes place at a global level as well as at a regional level. At a global level, empty containers are repositioned between ports. At a regional level empty containers are repositioned between importers, exporters, intermodal terminals, inland depots and one or more ports within a relatively small geographical area, namely the hinterland of ports. (Boile, Theofanis, Baveja, and Mittal 2008)

This paper focuses on empty container repositioning at a regional level. Currently, empty containers are often immediately transported back to a port. Several improvements to current practice are proposed in literature. Empty containers may be transported to inland depots for fulfilling future empty container requests in the hinterland. Street turns, transporting empty containers directly from an importer to an exporter, can reduce empty movements dramatically. Another option is to allow container substitutions (fulfilling the request for a certain type of container by supplying another type of container). Finally, container leasing may be used to reduce repositioning needs.

When addressing empty container repositioning at a regional level, several decisions have to be taken. These decisions belong to several planning levels: strategic, tactic and operational. In this research, operational decisions are considered. Optimization at this level means making sure that demand for empty containers is satisfied everywhere and that the most effective routes and transport modes are chosen. The underlying intermodal transportation network is assumed to be fixed. To account for interactions between the different decisions to be made, Crainic, Gendreau and Dejax (1993) note that ideally a single mathematical model should be developed. Considering the available Operations Research techniques at that time, the authors state that developing such a model is not feasible due to the complexity of the problem. Therefore, the operational planning problem is divided into two separate optimization problems, namely a container allocation and a vehicle routing problem.

Recently, some authors have proposed approaches to integrate both models. These approaches will be discussed in section 2.

The objective of this paper is to investigate the integration of container allocation and vehicle routing models. Mathematical models are formulated to show the benefit of an integrated approach. In section 2 of this paper a literature review concerning container allocation and vehicle routing models is given. Integration approaches proposed in literature are discussed. Section 3 contains the model formulations. Numerical results are presented in section 4. Finally, in section 5 conclusions are drawn and future research prospects are identified.

2. LITERATURE REVIEW

This section gives an overview of container allocation and vehicle routing models proposed in literature. Integration approaches are discussed.

2.1. Container Allocation Models

The objective of container allocation models is to determine the best distribution of empty containers, while satisfying both known and forecasted demand. (Crainic, Gendreau, and Dejax 1993) Empty container demand and supply should be taken into account. Besides, repositioning empty containers in order to be able to satisfy empty container requests in future periods should be considered. The most realistic model would be a stochastic, dynamic, multi-commodity model including container substitution, street turns and interdepot movements. Formulating and solving such an elaborate model is a challenging task. To our knowledge no such model is described in literature.

As mentioned in the introduction, this paper focuses on the repositioning of empty containers at a regional level. Therefore, only container allocation models related to this problem are discussed. For container allocation models concerning global or maritime repositioning of empty containers, often using simulation, the reader is referred to the corresponding literature. (Lai, Lam, and Chan 1995; Cheung and Chen 1998; Li, Leung, Wu, and Liu 2007; Lam, Lee, and Tang 2007; Di Francesco, Crainic, and Zuddas 2009; Dong and Song 2009)

A general framework for the regional allocation of empty containers is offered by Crainic, Gendreau and Dejax (1993). The authors describe a dynamic deterministic model for both the single and multi-commodity case. A stochastic model for the single commodity case is also formulated. In a subsequent work, Abrache, Crainic and Gendreau (1999) discuss a decomposition algorithm for the deterministic multi-commodity model formulated by Crainic, Gendreau and Dejax (1993).

Other mathematical models for empty container allocation are proposed by Chu (1995). Firstly, a single and a multicommodity dynamic deterministic model are described. Secondly, a dynamic two-stage and multi-

stage stochastic model for the single commodity case are formulated.

Olivo, Zuddas, Di Francesco and Manca (2005) develop an operational model for empty container management on a continental or interregional level by formulating it as a minimum cost flow problem. The model is dynamic and deterministic. Di Francesco, Manca and Zuddas (2006) take a similar modelling approach for the empty container allocation problem at a regional level. In a subsequent work, Di Francesco (2007) introduces the opportunity of short-term leasing into the model of Di Francesco, Manca and Zuddas (2006).

Jula, Chassiakos and Ioannou (2003) propose a static and a dynamic deterministic model with and without street turns and inland depots. Results show that when street turns are allowed and inland depots are used, costs drop significantly. Chang, Jula, Chassiakos and Ioannou (2006) introduce container substitution into the models of Jula, Chassiakos and Ioannou (2003). Next, the authors propose a model for the stochastic static single commodity problem, without container substitution.

A real-life application is discussed by Jansen, Swinkels, Teeuwen et al. (2004). The authors describe an operational planning system for the German company Danzas Euronet. Repositioning of empty containers is modelled as a minimum cost flow problem.

2.2. Vehicle Routing Models

Vehicle routing models aim to minimize overall transportation costs of both loaded and empty containers. The result of such a model is a set of vehicle routes which completely describe the loaded and empty movements to be executed during the next period. (Crainic, Gendreau, and Dejax 1993)

Literature on vehicle routing is extensive. Several sorts of problems exist and nomenclature is not always used in the same way. In this paper the classification of Parragh, Doerner and Hartl (2008) is followed. The authors distinguish two problem classes. The first class, called Vehicle Routing Problems with Backhauls (VRPB), is concerned with the transportation of goods from depots to linehaul customers and from backhaul customers to depots. The second class comprises models for the transportation of goods among customers. This class is denoted as Vehicle Routing Problems with Pickups and Deliveries (VRPPD). This research focuses on the second class of models since street turns cannot be considered by models of the first class. More precisely, this paper focuses on the classical Pickup and Delivery Problem (PDP), a subclass of VRPPD. With this type of problem, goods have to be transported between paired pickup and delivery locations. (Parragh, Doerner, and Hartl 2008)

A distinctive characteristic of this research is that full-truckload transportation, instead of the more extensively studied less-than-truckload problem, is considered. All vehicles are homogenous and have a

capacity of a single container. This means that the pickup and delivery activity of the same request should be performed immediately after each other. As a consequence, when all transportation requests are known, the problem can be modelled as an asymmetric Multi-Travelling Salesman Problem (m-TSP). (Mitrovic-Minic 1998; Ioannou, Chassiakos, Jula, and Unglaub 2002). However, when considering the integration of container allocation and vehicle routing, not all requests are known in advance. This increases integration complexity seriously. Therefore, in this paper the routing problem is formulated as a full-truckload Pickup and Delivery Problem. Similar problems are considered in literature. (Savelsbergh and Sol 1995; Mitrovic-Minic 1998; Cordeau, Laporte, Potvin, and Savelsbergh 2007; Huth and Mattfeld 2009)

2.3. Integration Approaches

Dejax and Crainic (1987) already suggested that the independent consideration of container allocation and vehicle routing neglects possible synergies arising from an integrated view on these problems. However, Crainic, Gendreau and Dejax (1993) stated that a single mathematical model comprising container allocations and vehicle routing would be computationally intractable.

Erera, Morales and Savelsbergh (2005) are of the opinion that, with current Operations Research techniques, a single model optimizing the operational planning is feasible. To verify this statement, the authors propose a deterministic multi-commodity model integrating routing and repositioning decisions for tank container operators. It is shown that the model may be solved by commercially available software for real-life cases. (Erera, Morales, and Savelsbergh 2005)

Huth and Mattfeld (2009) study the integration of container allocation and vehicle routing for the swap container problem (SCP). The swap container problem considers routing loaded swap containers and allocating and routing empty swap containers between hubs in a hub-to-hub transportation network. The problem is very similar to the problem considered in this paper. The main difference is that Huth and Mattfeld (2009) assume a truck capacity of two containers, while in this paper truck capacity is assumed to be a single container. Furthermore, the authors consider allocation and routing between hubs while here it is considered between depots, terminals and individual importers and exporters.

Three modelling approaches for the swap container problem are distinguished by Huth and Mattfeld (2009). First, with sequential planning (SP), no integration takes place. Empty container allocations are modelled by an allocation model and then inserted into a routing model. Loaded container transport requests are routed separately. The other two approaches represent different levels of integration and are based on the integration approaches of Geoffrion (1989, 1999). Functional integration (FI) combines given models through a coordination mechanism. Empty containers allocations

are modelled by an allocation model. Next, empty container allocations and loaded container transport requests are routed together. With the deep integration approach (DI), existing models are combined into a new model. Empty container allocations are modelled simultaneously with loaded and empty container routing. (Huth and Mattfeld 2009)

The authors propose formulations for all three approaches. Requests are represented by single containers and truck capacity is assumed to be two containers. It is shown that deep integration provides the best results, then functional integration and finally sequential planning. Huth and Mattfeld (2009) attribute the greater part of the advantage of integration to the opportunity of detouring and entrainment in the routing model (when transporting a single container, making a detour to include the transportation of another (empty) container may save costs).

Because in this paper, a truck capacity of a single container is assumed, detouring and entrainment are not feasible. Our objective is therefore to investigate whether in this case functional and deep integration still provide better results than sequential planning.

3. MODEL FORMULATION

In this section a basic container allocation and vehicle routing problem are formulated. Next, an integrated model is proposed. The objective is to illustrate the benefit of an integrated approach. Future research will focus on the extension of the models.

3.1. Container Allocation Model

The empty container allocation model proposed in this paper is a single commodity deterministic static model. Street turns are allowed. Only a single period is considered and thus no repositioning movements in order to be able to fulfil future requests are considered. The formulation is based on the static street turn depot-direct model of Jula, Chassiakos and Ioannou (2003). Parameter indices are slightly adapted to facilitate integration with the routing model and the constraints prohibiting interdepot movements are left out.

The network consists of consignees, shippers and depots. Consignees supply and shippers demand empty containers. Depots represent inland intermodal terminals. They may supply empty containers to shippers and may receive empty containers from consignees. For simplicity, it is assumed that depots have a sufficient stock of empty containers to fulfil all demands and do not request any empty containers themselves. Transportation costs are assumed to be proportional to transportation distances. Finally, the triangle inequality holds for the whole network. This means that a direct transport route between two nodes is at least as short/cheap as a route via an intermediate node. The following notation is used:

C = set of n consignees (index $1, \dots, n$)
 S = set of m shippers (index $n+1, \dots, n+m$)
 D = set of p depots (index $n+m+1, \dots, n+m+p$)
 $I = C \cup S \cup D$ = set of nodes
 $i, j \in I$
 $(i, j = 1, \dots, n, n+1, \dots, n+m, n+m+1, \dots, n+m+p)$
 c_{ij} = cost per unit of transport from node i to node j
 d_j = empty container demand at j ($j = n+1, \dots, n+m$)
 s_i = empty container supply at i ($i = 1, \dots, n$)
 x_{ij} = number of empty containers transported from i to j

The model may be formulated as follows:

$$\text{Min} \sum_{i=1}^{n+m+p} \sum_{j=1}^{n+m+p} c_{ij} x_{ij} \quad (1)$$

Subject to

$$\sum_{i=1}^n x_{ij} + \sum_{i=n+m+1}^{n+m+p} x_{ij} = d_j \quad \forall j = \{n+1, \dots, n+m\} \quad (2)$$

$$\sum_{j=n+1}^{n+m+p} x_{ij} = s_i \quad \forall i = \{1, \dots, n\} \quad (3)$$

$$x_{ij} \geq 0 \text{ and integer} \quad \forall i, \forall j \quad (4)$$

The objective function (1) minimizes variable costs related to distance travelled. Fixed vehicle costs are not considered. Constraint (2) makes sure demand of every shipper is satisfied by empty container coming from consignees and depots. Constraint (3) ensures that all empty containers supplied by consignees are allocated to be transported either to a shipper or to a depot. Finally, decisions variables are restricted to non-negative integer values by constraint (4).

3.2. Vehicle Routing Model

In this section the vehicle routing model is presented. All transportation requests, for both loaded and empty containers, are assumed to be known in advance. Multiple homogenous vehicles, initially located at a single depot, are considered. Vehicle capacity is a single container. Therefore, an arc-based as well as a node-based formulation may be used. Because integration with the allocation model is intuitively simpler for an arc-based model, this type of formulation is chosen. A disadvantage of this type of formulation is that each vehicle can visit each node at most once. Therefore, Huth and Mattfeld (2009) propose to introduce dummy nodes at the same location when multiple requests at a node exist.

The network underlying the vehicle routing model is very similar to the one proposed for the container allocation model. Only a single node, the vehicle depot, is added and the decision variables are now restricted to binary values. The notation is as follows:

C = set of n consignees (index $1, \dots, n$)
 S = set of m shippers (index $n+1, \dots, n+m$)
 D = set of p depots (index $n+m+1, \dots, n+m+p$)
 V = vehicle depot v (index 0)
 K = set of q vehicles
 $k \in K$ ($k = 1, \dots, q$)
 $I = C \cup S \cup D \cup V$ = set of nodes
 $i, j, l \in I$

$(i, j, l = 0, 1, \dots, n, n+1, \dots, n+m, n+m+1, \dots, n+m+p)$
 R = set of z transport requests (loaded and empty)
 r_{ij} = number of requests from node i to node j

$$z = \sum_{i=0}^{n+m+p} \sum_{j=0}^{n+m+p} r_{ij}$$

c_{ij} = cost per unit of transport from node i to node j

t_{ij} = transport time from node i to node j

FC = fixed cost per truck used

$$y_{ij}^k = \begin{cases} 1 & \text{if vehicle } k \text{ travels from node } i \text{ to node } j \\ 0 & \text{otherwise} \end{cases}$$

T_i^k = time epoch that vehicle k leaves node i

T_{\max} = maximum tour duration

The vehicle routing model may be formulated as follows:

$$\text{Min} \sum_{k=1}^q \sum_{i=0}^{n+m+p} \sum_{j=0}^{n+m+p} c_{ij} y_{ij}^k + \sum_{k=1}^q \sum_{j=1}^{n+m+p} y_{0j}^k FC \quad (5)$$

Subject to

$$\sum_{k=1}^q y_{ij}^k \geq r_{ij} \quad \forall i, \forall j \quad (6)$$

$$\sum_{i=0}^{n+m+p} y_{il}^k = \sum_{j=0}^{n+m+p} y_{ij}^k \quad \forall k, \forall l (i \neq l, j \neq l) \quad (7)$$

$$\sum_{j=0}^{n+m+p} y_{0j}^k = 1 \quad \forall k \quad (8)$$

$$\sum_{i=0}^{n+m+p} y_{i0}^k = 1 \quad \forall k \quad (9)$$

$$\sum_{j=0}^{n+m+p} y_{ij}^k \leq 1 \quad \forall i, \forall k \quad (10)$$

$$\sum_{i=0}^{n+m+p} y_{ij}^k \leq 1 \quad \forall j, \forall k \quad (11)$$

$$y_{ij}^k (T_i^k + t_{ij} - T_j^k) \leq 0 \quad \forall i, \forall j \neq 0, \forall k \quad (12)$$

$$T_i^k + y_{i0}^k t_{i0} \leq T_{\max} \quad \forall k, \forall i \quad (13)$$

$$T_0^k = 0 \quad \forall k \quad (14)$$

$$y_{ij}^k \text{ binary} \quad \forall i, \forall j, \forall k \quad (15)$$

This formulation assumes a truck capacity of a single container. The objective of the model is to minimize both fleet size and variable transportation costs. A large fixed cost per truck used is introduced to first minimize fleet size. Next, variable transportation costs are minimized (5). Constraint (6) ensures that at least as many vehicles travel between two nodes as there are requests between these nodes. No equality sign is used since vehicles are allowed to travel between two nodes for other purposes than fulfilling a request. Constraint (7) verifies that each vehicle entering a node also leaves that node. A vehicle should leave and enter the vehicle depot exactly once (constraints (8) and (9)). Each other node can be visited at most once by the same vehicle (constraints (10) and (11)). When a vehicle is not used, it stays at the vehicle depot, at a cost of zero ($y_{00}^k = 1$). Constraint (12) makes sure that when a vehicle leaves a node at a certain time, it cannot leave the following node after this time augmented with the travel time between the nodes. The objective of this constraint is to prevent loops in the tours and to keep track of tour duration (Parragh, Doerner, and Hartl 2008). A maximum tour duration is imposed by constraint (13). This maximum tour duration may represent a maximum working shift duration for the drivers. Constraint (14) sets the starting time of each vehicle at the vehicle depot to zero. Finally, constraint (15) makes sure that the decision variables only take on binary values.

Before the model can be solved efficiently, constraint (12) has to be linearized. This may be done as represented by constraint (16), with M a big number (for example the maximum tour duration).

$$(M + t_{ij})y_{ij}^k + T_i^k - T_j^k \leq M \quad \forall i, \forall j \neq 0, \forall k \quad (16)$$

3.3. Integrated Model

For the integrated model the same notation as for the vehicle routing model is used, except the following modifications and additions:

R = set of z loaded container transport requests

r_{ij} = number of loaded container transport requests from i to j

d_j = demand at node j ($j = n+1, \dots, n+m$)

s_i = supply at node i ($i = 1, \dots, n$)

x_{ij} = number of empty containers transported from i to j

Only loaded container transport requests are now known in advance. Empty container allocations are modelled by the integrated model, together with loaded and empty container routing. The empty container allocations made by the integrated model are shown by decision variables x_{ij} .

The formulation of the integrated model is very similar to the one of the vehicle routing model. Constraint (6) is replaced by constraint (17) which

ensures that at least as many vehicles travel between two nodes as the sum of loaded container transport requests and empty container allocations. Constraints (2-4) from the container allocation model are added. This results in the following formulation:

$$\text{Min} \sum_{k=1}^q \sum_{i=0}^{n+m+p} \sum_{j=0}^{n+m+p} c_{ij} y_{ij}^k + \sum_{k=1}^q \sum_{j=1}^{n+m+p} y_{0j}^k FC \quad (5)$$

Subject to

$$\sum_{k=1}^q y_{ij}^k \geq r_{ij} + x_{ij} \quad \forall i, \forall j \quad (17)$$

$$\sum_{i=0}^{n+m+p} y_{il}^k = \sum_{j=0}^{n+m+p} y_{lj}^k \quad \forall k, \forall l (i \neq l, j \neq l) \quad (7)$$

$$\sum_{j=0}^{n+m+p} y_{0j}^k = 1 \quad \forall k \quad (8)$$

$$\sum_{i=0}^{n+m+p} y_{i0}^k = 1 \quad \forall k \quad (9)$$

$$\sum_{j=0}^{n+m+p} y_{ij}^k \leq 1 \quad \forall i, \forall k \quad (10)$$

$$\sum_{i=0}^{n+m+p} y_{ij}^k \leq 1 \quad \forall j, \forall k \quad (11)$$

$$(M + t_{ij})y_{ij}^k + T_i^k - T_j^k \leq M \quad \forall i, \forall j \neq 0, \forall k \quad (16)$$

$$T_i^k + y_{i0}^k t_{i0} \leq T_{\max} \quad \forall k, \forall i \quad (13)$$

$$T_0^k = 0 \quad \forall k \quad (14)$$

$$\sum_{i=1}^n x_{ij} + \sum_{i=n+m+1}^{n+m+p} x_{ij} = d_j \quad \forall j = \{n+1, \dots, n+m\} \quad (2)$$

$$\sum_{j=n+1}^{n+m+p} x_{ij} = s_i \quad \forall i = \{1, \dots, n\} \quad (3)$$

$$y_{ij}^k \text{ binary} \quad \forall i, \forall j, \forall k \quad (15)$$

$$x_{ij} \geq 0 \text{ and integer} \quad \forall i, \forall j \quad (4)$$

4. COMPUTATIONAL RESULTS

The models formulated in the previous section are used to perform computational experiments on a small network. This network represents the pre- and post-haulage part of a larger maritime intermodal network and consists of nine nodes: three consignees (nodes 1, 2 and 3), three shippers (nodes 4, 5 and 6), two depots (nodes 7 and 8) and one vehicle depot (node 0). The two depots may represent intermodal terminals or container depots. The vehicle depot is assumed to be located near one of the depots, although this is no requirement. A graphic representation of the network is shown in figure 1. Maximum tour duration is set at 200. Dummy nodes are created when necessary. All models are solved with Lingo 10.0.

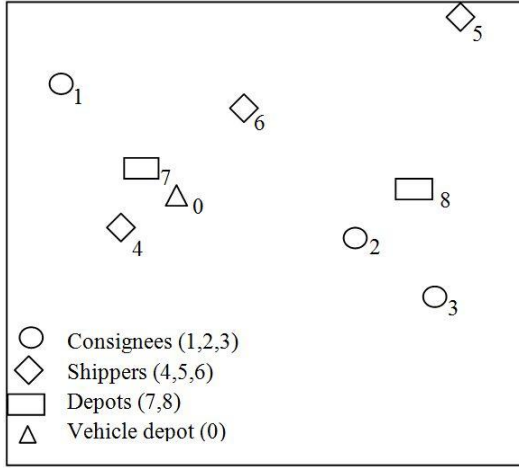


Figure 1: Network Representation

In total, ten problem instances are generated. The number of loaded container transport requests and empty containers supplied and demanded is kept relatively small to ensure limited computation times. The number of empty containers supplied and demanded by each consignee and shipper respectively, are generated randomly with a probability of 0.25 to be zero, 0.5 to be one and 0.25 to be two. Besides, six loaded container transport requests per problem instance are randomly generated. Because this paper focuses on the land transportation part of intermodal maritime container transport, all of these requests start or end at a depot. This means that no loaded containers are transported directly between shippers and consignees in the network. An overview of the problem instances is presented in table 1 and 2. Table 1 contains the empty container demand and supply. Columns two to four show the number of empty containers supplied by the three consignees. Columns five to seven show the number of empty containers demanded by each shipper. Table 2 presents the six loaded container transport requests for every problem instance.

Every problem instance is modelled according to the three integration approaches proposed by Huth and Mattfeld (2009) and discussed in section 2.3. Detailed results for the first problem instance are presented in the next section. Results of the other problem instances are discussed in section 4.2.

Table 1: Supply and Demand

| No. | Supply | | | Demand | | |
|-----|--------|---|---|--------|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 2 | 1 | 0 | 1 | 2 | 1 |
| 2 | 0 | 0 | 0 | 1 | 2 | 1 |
| 3 | 0 | 2 | 1 | 1 | 0 | 0 |
| 4 | 0 | 1 | 2 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 | 0 | 0 | 2 |
| 6 | 0 | 1 | 1 | 1 | 1 | 2 |
| 7 | 1 | 2 | 1 | 2 | 0 | 1 |
| 8 | 0 | 1 | 0 | 1 | 1 | 2 |
| 9 | 1 | 1 | 1 | 1 | 1 | 0 |
| 10 | 1 | 0 | 0 | 1 | 1 | 1 |

Table 2: Loaded Container Transport Requests

| No. | Loaded requests | | | | | |
|-----|-----------------|-----|-----|-----|-----|-----|
| | 4-7 | 4-8 | 5-8 | 6-7 | 8-1 | 8-2 |
| 1 | 4-7 | 4-8 | 5-8 | 6-7 | 8-1 | 8-2 |
| 2 | 4-7 | 4-8 | 6-7 | 6-8 | 7-2 | 8-3 |
| 3 | 4-7 | 6-8 | 7-1 | 7-2 | 7-3 | 8-1 |
| 4 | 4-8 | 5-7 | 6-8 | 7-2 | 8-3 | 8-3 |
| 5 | 4-7 | 4-8 | 6-7 | 6-8 | 8-1 | 8-3 |
| 6 | 4-7 | 6-7 | 7-1 | 7-3 | 8-1 | 8-3 |
| 7 | 4-7 | 5-8 | 7-1 | 7-3 | 8-3 | 8-3 |
| 8 | 4-8 | 7-1 | 7-1 | 7-2 | 7-3 | 8-2 |
| 9 | 6-8 | 6-8 | 7-1 | 7-2 | 7-3 | 8-2 |
| 10 | 5-8 | 6-7 | 6-7 | 6-8 | 7-2 | 8-2 |

4.1. Results of First Experiment

In this section results of the first problem instance are discussed in detail. The first step for the sequential planning (SP) and the functional integration (FI) approach is to model empty container allocations by the allocation model. Table 3 shows the results of this step. The first three allocations represent street turns or direct allocations between consignees and shippers. The last allocation is an empty container transport from a depot to a shipper.

Table 3: Empty Container Allocations (SP+FI)

| Origin | Destination | # Containers |
|--------|-------------|--------------|
| 1 | 4 | 1 |
| 1 | 6 | 1 |
| 2 | 5 | 1 |
| 8 | 5 | 1 |

With the sequential planning approach, empty container allocations and loaded container transport requests are routed separately. For the routing of empty container allocations, dummy nodes are introduced for nodes one and five. Routing the loaded container requests requires dummy nodes for nodes four, seven and eight. Results are shown in table 4 and 5. Together, four vehicles are required. Total variable transportation costs are €666.56.

Table 4: Vehicle Routes for Empty Containers (SP)

| Vehicle | Route | Cost |
|---------|-------------|--------|
| 1 | 0-2-5-8-5-0 | 193.24 |
| 2 | 0-1-4-1-6-0 | 149.52 |

Table 5: Vehicle Routes for Loaded Containers (SP)

| Vehicle | Route | Cost |
|---------|---------------|--------|
| 1 | 0-4-8-1-6-7-0 | 167.96 |
| 2 | 0-5-8-2-4-7-0 | 155.83 |

As described in section 2.3, the functional integration approach involves the simultaneous routing of empty container allocations and loaded container transport requests. The results of this approach for the first instance are shown in table 6. Due to the integration of the routing decisions, only three instead of four vehicles are needed. The third vehicle will even

be used less than half the time available. Furthermore, variable transportation costs are reduced by €182.21 to €484.34.

Table 6: Vehicle Routes (FI)

| Vehicle | Route | Cost |
|---------|-------------------|--------|
| 1 | 0-4-8-2-8-1-6-7-0 | 196.23 |
| 2 | 0-2-5-8-5-0 | 193.24 |
| 3 | 0-1-4-7-0 | 94.88 |

Finally, with the deep integration approach (DI), both allocation and routing decisions are fully integrated and modelled by a single model. Vehicle routes calculated by the integrated model are shown in table 7. As for the functional integration approach, only three vehicles are needed to satisfy all requests. Variable transportation costs for the deep integration approach are €453.31, which is respectively €213.25 and €31.04 lower than for the sequential planning and functional integration approaches.

For comparison purposes, empty container allocations made by the integrated model are shown in table 8. These container allocations differ from those proposed by the container allocation model (see table 2). Five container allocations are made, of which only two are street turns. Due to the simultaneous modelling of allocation and routing decisions, empty container allocations allowing for optimal vehicle routes are made.

Table 7: Vehicle Routes (DI)

| Vehicle | Route | Cost |
|---------|-------------------|--------|
| 1 | 0-7-5-8-1-7-0 | 196.43 |
| 2 | 0-4-8-5-8-2-4-7-0 | 179.85 |
| 3 | 0-1-6-7-0 | 77.02 |

Table 8: Empty Container Allocations (DI)

| Origin | Destination | # Containers |
|--------|-------------|--------------|
| 1 | 6 | 1 |
| 1 | 7 | 1 |
| 2 | 4 | 1 |
| 7 | 5 | 1 |
| 8 | 5 | 1 |

4.2. Other Results

An overview of results for all problem instances is presented in table 9. Column two, three and four show the total variable transportation costs for each integration approach. The last three columns show the number of vehicles required. Both variable routing costs and fleet size are always lower for functional and deep integration than for sequential planning.

In three cases, the functional and deep integration approach have the same results. In the seven other cases, deep integration causes lower variable transportation costs than functional integration. In these cases, empty container allocations made by the integrated model differ from those proposed by the container allocation model. Once the deep integration approach even results in a reduction of the number of

vehicles required compared to the functional integration approach. From these results may be concluded that more integration leads to better results.

Table 9: Overview of Results

| No. | Variable Costs | | | # Vehicles | | |
|-----|----------------|--------|--------|------------|----|----|
| | SP | FI | DI | SP | FI | DI |
| 1 | 666.56 | 484.34 | 453.31 | 4 | 3 | 3 |
| 2 | 565.79 | 440.57 | 440.57 | 4 | 3 | 3 |
| 3 | 574.09 | 462.53 | 447.75 | 4 | 3 | 3 |
| 4 | 687.82 | 413.91 | 389.10 | 4 | 3 | 2 |
| 5 | 542.24 | 363.47 | 363.47 | 4 | 2 | 2 |
| 6 | 626.05 | 533.42 | 471.84 | 4 | 3 | 3 |
| 7 | 655.66 | 423.96 | 423.15 | 4 | 3 | 3 |
| 8 | 577.84 | 472.96 | 472.96 | 4 | 3 | 3 |
| 9 | 719.85 | 562.89 | 510.84 | 5 | 3 | 3 |
| 10 | 496.95 | 365.52 | 357.68 | 4 | 2 | 2 |

5. CONCLUSIONS AND FUTURE RESEARCH

In order to satisfy demand for containers, empty containers have to be repositioned at a regional level between importers, exporters, intermodal terminals, inland depots and ports. Often, decisions on repositioning movements are based on a container allocation model, without taking into account vehicle routing.

This paper shows the advantage of integrating container allocation and vehicle routing decisions for the full-truckload problem with a truck capacity of a single container. Two approaches, functional integration and deep integration, may be used to integrate these decisions. First computational examples indicate that even for relatively small problem instances, both integration approaches result in smaller fleet size and significantly lower transportation costs. Best results are achieved with full integration of empty container allocation and vehicle routing decisions.

In future research an experimental design will be set up to determine which problem characteristics lead to the largest cost savings. Next, future research will focus on solution methods for larger problems and on the extension of the models presented in this paper. The container allocation model may be extended to a dynamic, multi-period model. This way repositioning movements in a certain period for fulfilling requests in a subsequent period may be modelled. Extra constraints, such as time windows for pickup and delivery of containers, may be imposed on the vehicle routing model. Finally, as node-based routing models are often computationally faster than arc-based routing models, future research will look at the opportunity of integrating the container allocation model with a node-based vehicle routing model.

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