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Vehicle routing under consideration of transhipment in horizontal coalitions of freight carriers

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Abstract

In order to reduce operational costs related to transportation activities in road haulage, small and medium-sized freight carriers can establish horizontal coalitions and share their resources. Through exchange of customer requests with other members within the coalition, carriers can improve the operational efficiency of their transportation processes. In this paper, transhipment is integrated into the conventional pickup and delivery problem in the collaborative context. Specifically, vehicles involved in transferring the same request are synchronized at the transhipment points. A mixed-integer programming model is proposed for this problem. Based on this model the benefits of transhipment are analysed. Computational results show considerable cost-savings enabled by transhipment in the operational planning of carrier coalitions.

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Keywords: Vehicle routing, transhipment, horizontal carrier coalitions, logistics

1. Introduction

Horizontal cooperation offers small and medium-sized freight carriers in road haulage a wide spectrum and potential of considerable benefits [1]. An important advantage of horizontal cooperation for carriers is to reduce their operational costs related to the fulfilment of customers' transportation requests. Through pooling their resources, i.e., customer requests and transportation capacities, more efficient routing plans can be generated while some requests are exchanged among different carriers within the coalition. Through exchange of customer requests, carriers can obviously improve their routing decisions and realize a cost reduction of up to 30% [2,3].

Besides request exchange, introducing transhipment can also be considered in the routing problems of horizontal carrier coalitions to further reduce the request fulfilment costs. While request exchange within horizontal coalitions has been studied in routing problems for different transportation scenarios [4-6], little research has been conducted on integrating transhipments into conventional routing problems in a collaborative context. The purpose of this paper is to consider this extension in the context of carrier collaboration and to evaluate the cost-saving potential embedded in the integration of transhipment into the routing decisions of carrier coalitions.

Introducing transhipment in vehicle routing enables transfers of goods among vehicles during the execution of customer transportation requests. In other words, the restriction that a single customer request for transportation is fulfilled by only one vehicle is relaxed. The most challenging problem is to synchronize the schedules of different vehicles. This extension of vehicle routing problems has attracted interest of several researchers in the last few years [7-10]. Two mixed-integer programming (MIP) models are proposed for the pickup and delivery problem with transfer (PDPT) [11,12] and a few solution approaches are also developed for this problem.

The places where transhipment is performed are referred to as *transhipment points* (TP). TPs can be specific facilities like depots of carriers or cross-docking centres, particularly when special equipment is needed for the transhipment operation.

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TPs can also be public places like parking areas or motorway service areas when the goods can be moved between vehicles without additional equipment. Depending on the place of transhipment, vehicles have to be differently coordinated. In the first case, the goods can be stored at the provided facilities before they are picked up again. It means that vehicles bringing goods from the pickup locations to the TPs do not have to wait there for the connecting vehicles, but can immediately leave the TPs. Thus, it has to be ensured that the goods are firstly transported from the pickup locations to the TPs before they can be further picked up at the TPs by another connecting vehicle. This is a *precedence* constraint associated with transhipment that must be considered. Particularly in the dial-a-ride problem with transfer (DARPT) [13] where persons are transported, a limitation of the maximal waiting time at the TPs for the connecting vehicles is mostly required. If the transhipment takes place at a public location without particular transhipment equipment, then the vehicles involved in the transferring process of a specific request have to meet each other. As a result, the schedules of both involved vehicles must be synchronised at the TPs. These *synchronisation* constraints are generally more restrictive than the precedence constraints.

Most studies on PDPT and DARPT are conducted based on the model proposed in [11] and consider precedence constraints and additional waiting time limits. In other words, vehicles need not wait for meeting the vehicles which are connected to them. In this paper, however, we consider the second case where vehicle routes (of different coalition members) must be synchronised: both vehicles fulfilling a single request must begin the transhipment at the same time and have the same operation time. The first restriction guarantees that the goods are being watched over by the truck drivers all the time. By introducing the second restriction, scheduling of the transhipment operations of several vehicles at the same place can be excluded from the problem and the increment of complexity associated with the synchronisation restrictions is limited. Particularly, the operation time for the transhipment is defined a priori as an estimation of an upper bound of the real operation time. This problem is referred to as the PDPT of carrier coalition (PDPTC).

This paper is organised as follows. In Section 2, an illustrative example is given for a better understanding of the cost reduction effect realized by considering request exchange as well as transhipment. A mathematical model for our PDPTC is proposed in Section 3. A computational study is conducted in Section 4 to validate the proposed model as well as to get some insight into the cost-savings of considering transhipment in the operational planning of carrier coalitions. Section 5 concludes the paper and gives an outlook over the future research in this area.

2. An illustrative example

We can consider a simple example to illustrate how collaboration can help carriers reduce the operational costs. Three scenarios are considered here: *isolated planning* (IP), *centralized planning* (CP), and *centralized planning with transhipment* (CPT).

In the scenario IP, each carrier in the coalition solves his PDPTW instance and the total costs of all carriers are summed up. In the second scenario CP, the multi-depot pickup and delivery problem with time windows (PDPTW) instance resulting for the entire coalition is solved. In the third and last scenario, the possibility of transhipment is considered by introducing additional nodes into the PDPTW instances representing the TPs and the PDPTC instances are solved.

Fig. 1 shows an example with two carriers and 6 pickup and delivery requests. The two depots of the carriers are depicted as the two squares noted with A and B. The solid lines represent the three requests (*r1*, *r2*, and *r3*) acquired by carrier A. The dashed lines represent the other three requests (*r4*, *r5*, and *r6*) of carrier B. Pickup locations are marked with plus signs and delivery locations with minus signs. The numbers given in the square brackets define the time window of the corresponding operation. The number on the right of the time window defines the service time.

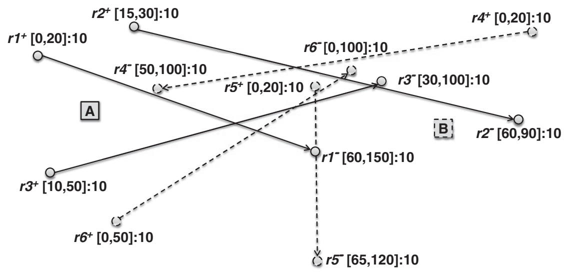

Fig. 1. An example with 2 carriers and 6 requests.

In the scenario of IP, i.e. without cooperation, each of the two carriers solves his own PDPTW and fulfils all his requests alone. The results of IP are given in Fig. 2. The total distances account to 138 distance units. The solid lines show the two vehicle routes of carrier A and the dashed lines depict those of carrier B.

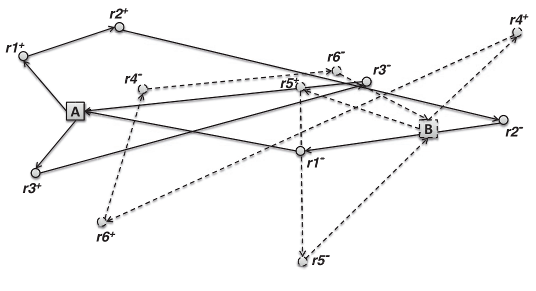

Fig. 2. Results without request exchange.

If the two carriers perform request exchange and make routing decisions together, they can solve the multi-depot PDPTW and obtain the results shown in Fig. 3 with the total distances of 131 units, i.e., a reduction of 7 distance units. In this case, request *r6* of carrier B is transferred to carrier A. It is fulfilled by the same vehicle which also serves request *r3*.

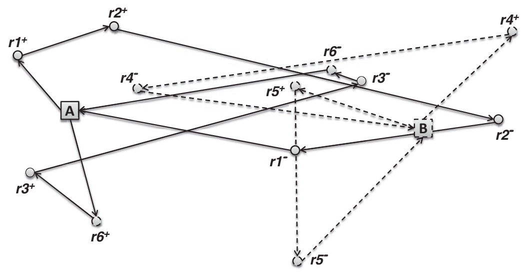

Fig. 3. Results with request exchange.

Now we can extend the scenario to CPT through introducing a TP into this example which is depicted in Fig. 4 as the triangle located almost at the centre between the two depots. In this case, the total travel distances of the coalition can be reduced to 125 distance units which indicates a further cost reduction of 6 units.

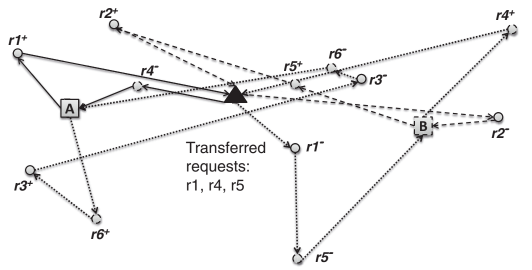

Fig. 4. Results with request exchange and transhipment.

The four vehicle routes in the routing plan comprising also the option of transhipment are given by:

- A — **r1**$^+$ — TP — **r4**$^-$ — A
- A — r6$^+$ — r3$^+$ — r3$^-$ — r6$^-$ — A
- B — **r4**$^+$ — TP — **r1**$^-$ — **r5**$^-$ — B
- B — **r5**$^+$ — r2$^+$ — TP — r2$^-$ — B

The three requests *r1*, *r4*, and *r5* that are shown with bold letters in the routes are transhipped: *r1* is now picked up by a vehicle of carrier A and brought to the TP. The same vehicle picks up the load of *r4* at the TP and transports it further to its delivery location. The vehicle of carrier B that picks up the loads of *r4* and unloads it at the TP picks up the loads of *r1* and finishes it. The third transhipped request *r5* is transferred between the two vehicles of carrier B.

3. A Mathematical model

The PDPTC can be described as follows. There are n transportation requests acquired from all carriers in the coalition. Each request $i \in R$ can be represented by a pickup location i, a corresponding delivery location $n+i$, and an amount of goods l_i to be transported. Specifically, it is defined that $l_{n+i} = -l_i$ for all requests $i \in P$. Let $P = \{1, \ldots, n\}$ and $D = \{n+1, \ldots, 2n\}$ be the sets of all pickup locations and delivery locations, respectively. Goods can be transferred from one vehicle to another at any of the τ TPs which are elements of the set $T = \{2n+1, \ldots, 2n+\tau\}$. A vehicle fleet $K = \{1, \ldots, m\}$ with sufficient capacities is available for the fulfilment of these requests. This fleet consists of all available vehicles of all coalition members. Each vehicle $k \in K$ has a limited capacity Q_k. The vehicles are stationed at different depots of the carriers. Let $o_k = 2n + \tau + k$ be the depot of vehicle k. We can define the set of vehicle depots as $O = \{o_1, \ldots, o_k\} = \{2n+\tau+1, \ldots, 2n+\tau+m\}$. The PDPTC can be defined on a graph $G = (N, A)$, where $N = P \cup D \cup T \cup O$ is the set of nodes and $A = N \times N$ is the set of arcs. Each arc $(i, j) \in A$ is associated with a travel distance d_{ij} and a travel time d'_{ij}. Without loss of generality, it is further assumed that $d'_{ij} = d_{ij}$. Each node $i \in N$ is associated with a time window $[a_i, b_i]$ and a service time s_i. Operations must be started within the given time windows.

It is further assumed that each request is allowed to be transferred no more than once. A vehicle can visit as many TPs as necessary. Capacities of TPs are assumed to be unlimited. Neither fixed costs nor variable costs have to be considered due to transhipment since TPs are assumed to be public and freely accessible. The objective of the PDPTC is to fulfil all customer requests of the coalition in such a way that the total driven distances are minimized.

Following decision variables are needed to formulate the MIP model for the PDPTC: binary variable x_{ijk} will be one if vehicle $k \in K$ travels the arc $(i, j) \in A$. Binary variable y_{ik} will be one if node $i \in N$ is served by vehicle $k \in K$. Binary variable $z^{(+)}_{iuk}$ is one if the goods of request $i \in P$ are picked up by vehicle $k \in K$ at node i and unloaded at TP $u \in T$. Similarly, binary variable $z^{(-)}_{iuk}$ is one if the goods of request $i - n \in P$ are picked up by vehicle $k \in K$ at a TP $u \in T$ and transported to its delivery node $i \in D$. Additionally, variable t_{ik} and L_{ik} define the start time when the node $i \in N \setminus O$ is served by vehicle $k \in K$ as well as the load status after k finishes the service at i. The model is then given as follows:

$$\min \sum_{(i,j)\in A} \sum_{k \in K} d_{ij} x_{ijk} \tag{1}$$

$$\text{s.t.} \sum_{j \in N} \sum_{k \in K} x_{ijk} = 1 \quad \forall i \in N \setminus T \tag{2}$$

$$\sum_{i\in N} x_{ijk} - \sum_{i\in N} x_{jik} = 0 \quad \forall j \in N, k \in K \tag{3}$$

$$\sum_{j\in P\cup T\cup\{o_k\}} x_{o_k jk} = \sum_{i\in D\cup T\cup\{o_k\}} x_{io_k k} = 1 \quad \forall k \in K \tag{4}$$

$$x_{iik} = 0 \quad \forall i \in N \setminus O, k \in K \tag{5}$$

$$\sum_{i\in N} x_{ijk} = y_{jk} \quad \forall j \in N, k \in K \tag{6}$$

$$\sum_{u\in T}\sum_{k\in K} z_{iuk}^{(+)} \le 1 \quad \forall i \in P \tag{7}$$

$$\sum_{k\in K} z_{iuk}^{(+)} = \sum_{k\in K} z_{i+n,u,k}^{(-)} \quad \forall i \in P, u \in T \tag{8}$$

$$y_{ik} \le \sum_{u\in T} z_{iuk}^{(+)} + y_{i+n,k} \le 1 \quad \forall i \in P, k \in K \tag{9}$$

$$y_{i+n,k} \le \sum_{u\in T} z_{i+n,u,k}^{(-)} + y_{ik} \le 1 \quad \forall i \in P, k \in K \tag{10}$$

$$y_{uk} \ge z_{iuk}^{(+)} \quad \forall i \in P, u \in T, k \in K \tag{11}$$

$$y_{uk} \ge z_{i+n,u,k}^{(-)} \quad \forall i \in P, u \in T, k \in K \tag{12}$$

$$x_{ijk} = 1 \Rightarrow t_{ik} + d'_{ij} + s_i \le t_{jk}$$
$$\forall i \in N, j \in N \setminus O, k \in K : i \ne j \tag{13}$$

$$t_{i+n,k} \ge t_{ik} + s_i \quad \forall i \in P, k \in K \tag{14}$$

$$t_{i+n,k} \ge t_{ih} + s_i \quad \forall i \in P, k, h \in K : h \ne k \tag{15}$$

$$y_{ih} = y_{i+n,k} = 1 \Rightarrow t_{uh} = t_{uk}$$
$$\forall i \in P, u \in T, k, h \in K : k \ne h \tag{16}$$

$$z_{iuk}^{(+)} = 1 \Rightarrow t_{ik} + s_i \le t_{uk} \quad \forall i \in P, u \in T, k \in K \tag{17}$$

$$z_{i+n,u,k}^{(-)} = 1 \Rightarrow t_{uk} + s_u \le t_{i+n,k} \quad \forall i \in P, u \in T, k \in K \tag{18}$$

$$a_i \le t_{ik} \le b_i \quad \forall i \in N \setminus O, k \in K \tag{19}$$

$$L_{ik} = 0 \quad \forall i \in O, k \in K \tag{20}$$

$$l_i \le L_{ik} \le Q_k \quad \forall i \in P, k \in K \tag{21}$$

$$0 \le L_{i+n,k} \le Q_k - l_i \quad \forall i \in P, k \in K \tag{22}$$

$$x_{ijk} = 1 \Rightarrow L_{ik} + l_j = L_{jk} \quad \forall i \in N, j \in N \setminus T, k \in K \tag{23}$$

The objective function (1) minimises the total driven distances of all vehicles. Constraints (2) and (3) enforce that each node except the TPs is visited exactly once. Vehicles must start and end their routes at their own depots. This is guaranteed by constraint (4). Constraint (5) forbids self-cycles for all nodes except for the depots. Constraint (6) ensures that $y_{jk} = 1$ only when vehicle *k* serves node *j*.

The following six constraints are imposed for the transhipment. The left-hand-side of Constraint (7) calculates the number of transhipments related to a request and forces it to be no more than one. Thereby it is ensured that each request can be transhipped at most once. Constraint (8) ensures that if a request is transported by some vehicle to a TP for transhipment, it must be picked up at this TP by some vehicle again. However, Constraint (8) does not forbid that a request will be planned as transhipped at some TP but actually fulfilled by the same vehicle. This case is then excluded by the next two constraints. Constraints (9) and (10) ensure that if a vehicle visits a pickup/delivery node, it must either serve the corresponding delivery/pickup node too or deliver/pick up the loads to/from some TP. Constraints (11) and (12) enforce vehicles to visit TPs if they are used to tranship some requests at these TPs.

Constraint (13) specifies the time when services start. The precedence restriction related to a single request is satisfied by Constraint (14) in cases without transhipment and by (15) with transhipment. Constraint (16) is the synchronisation constraint. It enforces that if two different vehicles are used for the transhipment of a request, the start time of the transhipment must be exactly the same for both vehicles. Constraints (17) and (18) are the precedence constraints valid for requests which are to be transhipped. Constraint (17) enforces that if a request is to be transported for transhipment by a vehicle to some TP, the unloading operation at the TP must happen after the goods have been completely loaded at the pickup location. Constraint (18) is valid for the second part of the fulfilment of a transhipment request. Time window restrictions are satisfied by constraint (19). Constraint (20) enforces that the vehicles start their routes with null loads. Constraints (21) and (22) ensure that the capacity restrictions related to vehicles are not violated. The last constraint (23) calculates the exact load status of vehicles after serving each node except TPs. Since the load statuses at all depots are zero, there is no need to introduce additional flow balancing constraints for the TPs.

4. Computational study

In this section, a computational study is conducted to evaluate the benefits of considering transhipments in the routing decision of carrier coalitions. Some new instances are generated for this purpose. The total costs of the coalition for the three scenarios IP, CP and CPT are then calculated by solving the corresponding MIP models. All instances are solved on an Intel Core i7-740QM PC with 4GB memory using IBM ILOG CPLEX 12.5.

Transhipment should be considered for reducing costs especially when the pickup and delivery locations of requests are distributed on different sides of the chosen TPs as the case depicted in the example in Section 2. We have generated two sets (R and P) à 10 instances that are similar to this example. Each instance consists of two carriers, nine requests and one TP. One vehicle is available for each carrier.

All pickup and delivery nodes of the instances are scattered in a square 150×150. The two depots of the two carriers are located in the middle of the left side as well as the right side of the square while the TP is located at the centre. The exact coordinates of the depots and the TP are shifted randomly a little bit for each instance. For Set R, the pickup and delivery locations related to a single request are generated as follows. The pickup location is randomly chosen in the entire square. The delivery location is then randomly chosen on the line defined by the pickup location and the centre point of the square, but, in relation to the pickup location on the opposite side of the centre point. For Set P, the pickup locations are randomly generated like for Set R, except that no locations in the middle of the square (x-coordinate between 60 and 90) are chosen.

Time windows of the requests are generated also randomly. The time window of the TP is set open. The service time of a pickup/delivery operation is defined as 10 while the service time at the TP is set to 30.

The optimal solutions for all tested instances found by CPLEX are reported in Table 1 and Table 2. For every instance, the computing time required was less than one minute. The total costs (TC_{IP}) of the coalition in the IP scenario are obtained by summing up the individual costs of all carriers. The coalition's total costs (TC_{CP}) of CP are the costs without transferring any requests. The absolute cost-savings ΔTC_1 are given as the difference between TC_{IP} and TC_{CP} ; the relative cost-savings are determined as $(TC_{IP} - TC_{CP}) \cdot 100 / TC_{IP}$. Table 1 shows the results for Set P and Table 2 for Set R.

Table 1. Cost-savings through request exchange of Set P

Instance	TC_{IP}	TC_{CP}	ΔTC_1	ΔTC_1(%)
P 01	1647.30	1207.36	439.94	26.71
P 02	1500.89	1084.71	416.19	27.73
P 03	1312.01	990.55	321.47	24.50
P 04	1580.87	1272.36	308.51	19.52
P 05	1149.27	1071.40	77.86	6.78
P 06	1172.48	1172.48	0.00	0.00
P 07	1513.04	1241.96	271.08	17.92
P 08	1487.90	1202.66	285.24	19.17
P 09	1329.76	1083.34	246.41	18.53
P 10	1248.28	903.74	344.53	27.60
Avg.	1394.18	1123.06	271.12	18.85

It can be seen that the total costs of the coalition has been considerably reduced through reassigning requests among the coalition members. For Set P, the realized cost-savings account to 271.12 distance units on average, which correspond to 18.85% of the total costs without request exchange. Cost-savings of the similar range have also been reached for Set R: 275.65 distance units respectively 19.42% on average. The maximum value for synergies through request is 33.44% (R 05).

Table 2. Cost-savings through request exchange of Set R

Instance	TC_{IP}	TC_{CP}	ΔTC_1	ΔTC_1(%)
R 01	1452.47	1265.18	187.29	12.89
R 02	1411.35	1111.28	300.07	21.26
R 03	1243.48	998.65	244.83	19.69
R 04	1044.76	888.00	156.76	15.00
R 05	1578.40	1050.51	527.89	33.44
R 06	1510.50	1219.85	290.64	19.24
R 07	1207.11	1107.21	99.90	8.28
R 08	1495.86	1140.32	355.54	23.77
R 09	1570.52	1183.92	386.60	24.62
R 10	1291.12	1084.17	206.95	16.03
Avg.	1380.56	1104.91	275.65	19.42

The following results indicate the potential of further cost reductions by transferring requests at a TP. In Table 3 and Table 4 the total costs (TC_{CPT}) of the coalition are stated for the same P and R sets with an additional TP node. Similar to ΔTC_1 , the cost-savings ΔTC_2 are shown as the difference between TC_{CP} and TC_{CPT} as an absolute value and a relative value. The numbers of transhipped requests in each instance are given in the last column.

Table 3. Cost-savings through integration of transhipment of Set P

Instance	TC_{CPT}	ΔTC_2	ΔTC_2(%)	Transhipped requests
P 01	1186.11	21.25	1.76	1
P 02	1084.71	0.00	0.00	0
P 03	912.33	78.22	7.89	5
P 04	1258.18	14.18	1.11	4
P 05	942.27	129.13	12.05	5
P 06	1099.00	73.48	6.27	4
P 07	1205.70	36.26	2.92	4
P 08	1126.04	76.62	6.37	5
P 09	1083.34	0.00	0.00	0
P 10	860.71	43.04	4.76	6
Avg.	1075.84	47.22	4.13	3.4

The results demonstrate that the total fulfilment costs can be further reduced by introducing transhipment. For Sets P and R, the average cost-savings additionally realized by transhipment are 47.22 and 17.15 distance units, respectively. It can be observed that transhipment is not used in the PDPTC solutions for all instances. If we only consider the instances with transhipped requests, the average cost reduction increases from 4.13% to 4.25% for Set P and from 1.56% to 2.65% for Set R.

Table 4. Cost-savings through integration of transhipment of Set R

Instance	TC_{CPT}	ΔTC_2	ΔTC_2(%)	Transhipped requests
R 01	1265.18	0.00	0.00	0
R 02	1081.85	29.43	2.65	1
R 03	998.65	0.00	0.00	0
R 04	867.83	20.18	2.27	4
R 05	1015.06	35.45	3.37	3
R 06	1188.68	31.18	2.56	3
R 07	1107.21	0.00	0.00	0
R 08	1133.03	7.29	0.64	4
R 09	1183.92	0.00	0.00	0
R 10	1036.18	47.99	4.43	2
Avg.	1087.76	17.15	1.59	1.7

The computational results of Table 1 and Table 2 confirm the expected cost reductions due to request exchange. Moreover, operational request fulfilment costs of freight carriers can be further reduced using the possibility of transhipment. Transhipment is not used in every instance as a consequence of stringent time windows. A comparison between the results of the two instance sets indicates that more costs can be reduced by transhipment for Set P than for Set R. Also the average number of transhipped requests of Set P is higher than of Set R. It can be concluded that if the loads of customer requests are to be transported mainly between some major regions, carrier coalitions should install transhipment to explore additional potential of cost reduction.

5. Conclusion

In this paper, the possibility of transhipment is introduced to the classical PDPTW in the context of horizontal collaboration of freight carriers. A mathematical model that can be easily translated into a MIP model by eliminating if-then constraints is presented for the extended problem PDPTC. In particular, vehicles involved in the transhipment of a specific request are synchronised in this model.

In order to evaluate the potential of cost-savings enabled by transhipment, some test instances have been generated for the computational study. Three scenarios are considered in the computational study: the isolated planning scenario, in which no request is exchanged, the collaborative scenario, where a centralized plan is made for the entire coalition and the collaboration scenario with the possibility of transhipment. Computational results show that collaboration achieves significant cost-savings compared to the isolated planning. Additional savings can be reached by introducing the possibility of transhipment.

The required time to find the optimal solutions in our computational study is relatively short. However, already small extensions such as the introduction of open time windows result in significantly longer computing times even for the same instances tested in our computational study. As well expansions like several TPs, more participants in the coalition or a fleet of vehicles per freight carrier should be integrated in the instances to analyse the impact on vehicle routing. Thus, efficient and effective heuristic approaches have to be developed for the PDPTC in future research, which can be used for the evaluation of the cost-saving potential through transhipment with larger instances. In addition, more tests should be performed to identify other factors that influence such potential reachable by transhipment. Furthermore, decentralized solution approaches suitable for collaborative planning where each carrier preserves its own decision-making competences and private information should be established.

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