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REGULAR ARTICLE

Collaborative transportation planning of less-than-truckload freight

A route-based request exchange mechanism

Xin Wang · Herbert Kopfer

Abstract Collaborative transportation planning (CTP) within a coalition of small and medium-sized freight carriers can be used as a powerful instrument to improve the operational efficiency of the coalition members. In such coalitions, transportation requests from different carriers are exchanged in order to reduce the total fulfillment costs. In this paper, the CTP for a set of independent carriers exchanging less-than-truckload transportation requests is considered. The realistic restriction that all collaborating partners have only limited capacities in their fleets is included in the consideration. To keep their autonomy, coalition members keep their sensitive information including customer payments and cost structures unexposed during CTP. A new decentralized request exchange mechanism for CTP is proposed while only vehicle routes are considered for exchange. It is tested on some newly generated instances and the CTP solutions are compared with those obtained by isolated planning without collaboration and those obtained by a heuristic approach for the centralized planning problem. The results indicate that our mechanism is very efficient and effective in terms of realizing potential cost-savings by CTP, even when capacity limitations and restrictions on the exposure of information are explicitly considered.

Keywords Collaborative transportation planning · Request exchange · Freight carrier coalition · Request selection and pickup and delivery problem with time windows

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1 Introduction

Freight carriers are confronted with increasing pressure to improve profitability, while it is difficult for them to further reduce operational costs. For small and medium-sized freight carriers (SMC), horizontal collaboration is considered as a promising support. Cruijssen et al. (2007c) notice that more and more horizontal cooperation initiatives are developing in practice and give a general literature review on this topic.

Early research on horizontal cooperation of independent freight carriers can be found in Kopfer and Pankratz (1999), where such coalitions are referred to as groupage systems (GS). Transportation planning within a GS is not executed by each participant separately but in a concerted fashion, which is referred to as collaborative transportation planning (CTP). CTP intends to improve the planning situation of coalition members while preserving their autonomy. According to Stadtler (2009), collaborative planning can be understood here as a joint decision-making process for aligning plans of individual GS members with the aim of achieving coordination in light of information asymmetry. The specific goal of CTP is to achieve a reallocation of requests among the carriers, with the effect that the total fulfillment costs are smaller than the sum of the carriers' individual costs without collaboration. The obtained cost savings present the joint benefits of the coalition that cannot be achieved individually. These joint benefits are then to be shared by the members in such a way that all freight carriers in the GS will improve their profitability.

In this paper, a scenario of CTP is investigated while some complex realistic restrictions are being considered. We study the CTP of a set of independent freight carriers fulfilling less-than-truckload (LTL) pickup and delivery transportation requests with time windows. These requests can be fulfilled by any member of the GS and thus can be exchanged among members of the GS. We consider the static planning situation, where all relevant information is available at the beginning of the planning. This means that the underlying routing problem of our research is the pickup and delivery problem with time windows (PDPTW) (Dumas et al. 1991). During CTP, the autonomy of partners must be protected. This primarily concerns private sensitive information and decision-making competences. Thus, customer payments and cost structure information are unexposed in the CTP. Additionally, all participants can make decisions following their own preferences (e.g., balancing drivers' workloads).

In order to explore the synergy effects reachable by combining complementary requests of different carriers into bundles, exchange mechanisms for request reallocation in CTP scenarios are introduced. An important issue in the design of a solution approach allowing the exchange of requests is to deal with the construction of bundles. First of all, carriers can theoretically take into account every possible combination of requests for exchange, which makes the number of bundles of requests to be considered exponentially large. Furthermore, it is very difficult for a carrier to exactly evaluate his fulfillment costs for all possible combinations of requests independent of other requests, especially for LTL pickup and delivery requests with time windows. This evaluation is the basis of determining the *ask price*, which is the lowest price the carrier will charge for the execution of all requests included in a bundle. It seems that the ask price for a single request or a bundle of requests can be estimated by calculating the incremental cost, which is the difference between the total fulfillment

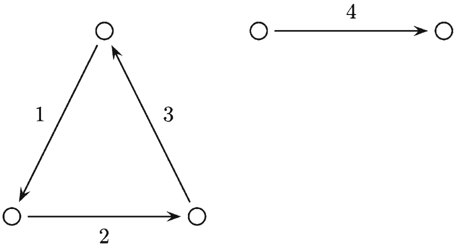

Fig. 1 Request bundling in the transportation service procurement problem

costs of routing plans with and without this request/bundle. This approach presumes that everything else in the underlying tour remains unchanged. However, since the outcome of the exchange process is unpredictable, it is impossible for carriers to know which requests will remain unchanged. In other words, it is not clear based on which request portfolio the incremental costs of a request or a bundle should be calculated.

In the transportation service procurement problem (TSPP), a similar problem of bundling and evaluating requests is studied, for which a combinatorial auction (CA) is proposed instead of using a series of single-item auctions (Song and Regan 2005; Lee et al. 2007). The bid construction problem in TSPP appears to be similar to the problem at hand, yet the ideas proposed in Song and Regan (2005) and Lee et al. (2007) are not applicable to the CTP scenario considered in this paper. In the TSPP, shippers buy transportation services on several lanes from some carriers. A lane corresponds to a service on a transportation relation specified by an origin, a destination and a flow of goods which are to be transported from the origin to the destination during a predefined time interval. Different from an LTL request which has to be served only once on the operational level, a lane usually needs to be served frequently over a long period and thus belongs to the strategic planning level. Carriers can bid on these lanes for certain prices. The shippers choose those bids which minimize the total costs. Because bundling lanes may result in less empty miles as well as less travel and repositioning costs, shippers can reduce their procurement costs. Figure 1 illustrates this situation. Since lanes 1, 2, and 3 constitute a closed route without empty driven miles, carriers can bid on this bundle of lanes for a lower price than the total prices of three single-item bids, each containing only one of these three lanes. On the other hand, lane 4 can hardly be combined with other lanes, it may be left unassigned in the CA and be auctioned later in a single-item auction. In contrast to the TSPP, the problem of having requests unassigned may have serious consequences in the CTP scenario, since the carriers are both seller and purchaser at the same time. Figure 2 illustrates this problem. Suppose two carriers A and B try to exchange requests through a CA. Each of them has a vehicle that can serve up to three customers. Before the exchange, all six customers can be served (Fig. 2a). Since request 4 lies in the near of request 2 and 3, Carrier A may bid on the bundle including requests 1, 2, and 4. Carrier B may bid on the bundle of requests 5 and 6 since they can be well consolidated in his route. None of the two carriers A and B would bid on request 3. The result would be that Carrier A wins the bundle with requests 1, 2, and 4, Carrier B wins the bundle with requests 5 and 6, and request 3 is returned to Carrier A. In this case, the total fulfillment costs for requests 1, 2, 4, 5, and 6 are reduced through the CA. However, because of the

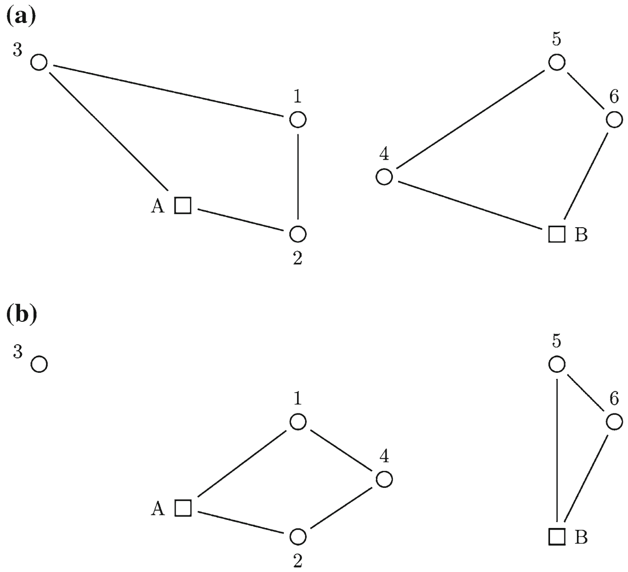

Fig. 2 Routing plan before (**a**) and after (**b**) request exchange

capacity limitation, Carrier *A* cannot fulfill in a single tour all four requests assigned to him. In order to get request 3 fulfilled, extra capacity is needed (e.g., by installing an additional tour or by subcontracting), which usually is very expensive and may shoot down the benefits reached by request exchange.

In this paper, we propose a route-based request exchange mechanism for CTP in GSs. The aim is to generate CTP solutions whose efficiency is close to that of centralized planning, while the complexity of the request exchange process is relatively low and the possible negative influence on post-exchange planning illustrated in Fig. 2b is already considered within the mechanism itself. In contrast to previously proposed approaches for CTP, the mechanism introduced here concentrates on complete routes instead of arbitrary bundles or single requests. We use a set partitioning model for the routing problem of the GS. The carriers generate vehicle routes independently of each other and submit these routes to an agent of the GS that practically can be just a computer. Based on the routes submitted by the carriers, the agent solves the problem of looking for a composition that minimizes the total fulfillment costs. The carriers iteratively generate and submit new routes based on the feedback information from the agent, which is deduced from the dual values of a linear relaxation of a set partitioning problem (SPP). From a methodological point of view, the high efficiency and effectiveness of our approach is reached due to the fact that, from the entire coalition's point of view, our strategy for building transportation plans has some strong similarities to the column generation approaches for vehicle routing (Dumas et al. 1991; Sigurd et al. 2004).

The remainder of this paper is organized as follows. Section 2 gives a review of research on CTP. The CTP problem considered in this paper is formally defined in

Sect. 3. The route-based request exchange mechanism is presented in Sect. 4 and subsequently tested on some newly generated instances in Sect. 5. In order to evaluate the efficiency achieved by our collaborative approach, the CTP solutions are compared to those obtained by isolated planning without collaboration and those obtained by centralized planning. Finally, some conclusions are drawn in Sect. 6.

2 Literature review

Horizontal collaboration of independent freight carriers has attracted substantial interest of researchers in the last few years. It is recommended that SMC should use CTP to increase efficiency. Estimations of the reachable cost reduction through CTP are up to 30 % and estimations of the decrement of used vehicles are between 7.3 and 10 % (Cruijssen and Salomon 2004; Cruijssen et al. 2007a; Krajewska et al. 2008). The standard method used for determining the cost-saving potentials is to calculate the cost differences between isolated planning and centralized planning. An empirical study by Cruijssen et al. (2007b) indicates the potential benefits as well as some impediments of horizontal cooperation in logistics. Based on a case study and simulations, Cruijssen and Salomon (2004) discuss some influencing factors of request sharing and the impact of request sharing on clients, collaborating companies and the society. Wang and Kopfer (2011) analyze both potentials of cost-savings for carriers in GSs and challenges for future research on CTP.

Although the benefit of CTP is widely recognized, cooperation cannot function without an adequately designed system of mechanisms. Krajewska and Kopfer (2006) propose a general framework for the design of a complete CTP model which includes three phases: preprocessing, profit optimization and profit sharing. The main task in the preprocessing phase is to identify customer requests suitable for exchange and to specify the payments for transferring them to partners. Profit optimization aims to find out a mapping between requests offered for exchange and collaborating partners, so that the joint profits of the entire coalition are maximized. In the third phase, the joint profits achieved through exchanging requests are distributed to the partners according to a profit sharing scheme taking fairness criteria into account.

Krajewska and Kopfer (2006) design a request exchange mechanism based on the concept of CA. They do not assume any specific routing problem for their CTP model. They presume that the fulfillment costs for any combination of requests can be exactly evaluated. However, the calculation of the potential fulfillment costs for all bundles of LTL pickup and delivery requests with time windows constitutes a very difficult problem, which they do not consider. This problem increases even further when limitations of capacities are considered and post-exchange planning is to be performed.

Schwind et al. (2009) propose an exchange mechanism for profit centers of a single company. The problem they consider is the vehicle routing problem with time windows (Cordeau et al. 2002). It enables the selection of only requests located between pairs of adjacent profit centers for exchange and leaving the rest requests near the depots not for exchange. The marginal costs of each single bid, i.e., the cost difference between the routing results including and excluding the requests in the bid with those own requests that are not offered for exchange, is calculated as bid price.

In the request exchange mechanisms developed by Berger and Bierwirth (2010) for inter-organizational scenarios, the exposure of information is limited. An important simplification of their approach is the consideration of a pickup and delivery problem without capacity restriction, also known as the traveling salesman problem with precedence constraints (PDTSP) (Renaud et al. 2000). They test both a Vickrey auction (Vickrey 1961) and a CA for request exchange. Although restricting circumstances of capacity limitations do not exist in the PDTSP investigated by them, the auctions performed with their approaches can only realize on average 18.2–64.8 % of the cost-saving potentials for different test sets.

Schönberger (2005) proposes a mechanism considering a variation of the PDPTW, where each partner has only one vehicle with unlimited capacity. Since time windows have been introduced, no single partner can execute all requests. Requests that cannot be planned within the GS are subcontracted. He also uses CA as exchange mechanism. Each participant solves a combined problem of request selection and PDPTW to maximize their own profits. They dispense the resulting routes as bids. The shortcoming of this design is that all information has to be exposed, which is a critical issue for a GS.

Özener et al. (2011) study the lane exchange among FTL carriers and propose bilateral exchange mechanisms based on the calculation of marginal costs of serving single lanes. Their computational experiments show that for the relevant setting to our scenario *no information sharing with side payments*, their approach can only realize about 30 % of the potential cost-savings.

3 Collaborative transportation planning

Suppose a GS of m independent freight carriers. Each freight carrier i comes along with a request portfolio R_i containing $n_i, i = 1, \ldots, m$, LTL pickup and delivery requests with time window restrictions, which are supposed to be offered for exchange in the GS. A fleet K_i with k_i homogeneous vehicles in terms of both cost rates and loading capacity is positioned at the depot of each coalition partner i. However, the cost rates and loading capacities of vehicles need not be the same for different participants. All requests can be exchanged and fulfilled by any vehicle in the coalition. In this paper, we consider the situation of cooperating carriers on an operational (day-to-day) planning level. The proposed approach in Sect. 4 can also be applied to tactical planning situations, e.g., to applications in transport contract tendering.

Although integrating subcontracting and vehicle routing may reduce the fulfillment costs (Krajewska and Kopfer 2009; Kopfer and Wang 2009), it is assumed that, in the isolated planning scenario, all partners have enough capacity in their fleets; i.e., they can execute their whole original request portfolios R_i with their own fleets K_i. As a consequence, subcontracting on the level of single partners of the GS is not considered in this research. This assumption is made to keep the demonstration of the route-based request exchange mechanism simple and straightforward. Please note that the CTP approach can also be applied when the participating freight carriers have more transportation volume in the isolated planning scenario than they can fulfill with their own fleet and thus have to subcontract remaining requests to external carriers.

After the request exchange, partners will be assigned new request portfolios and it can no longer be guaranteed that all requests can still be fulfilled in the routes of the collaborative solution (Fig. 2b). That is why, potentially, subcontracting may have to be performed by the agent on the level of the entire GS for those requests that cannot be fulfilled in the GS anymore. It is further assumed that all partners agree to the concerted goal to maximize the total profit of the coalition in the preprocessing and profit optimization phase while profit sharing is considered as a separate challenging task, which is mainly to be tackled by developing adequate profit sharing strategies. Participants are not expected to expose their private information to the agent nor to other partners. This means that no centralized planning is possible.

The CTP problem together with the isolated and centralized planning can be defined as follows. Each carrier i can serve his requests R_i following his own routing plan Π_i with costs C_i by solving a PDPTW which can be defined based on Desaulniers et al. (2002) and Ropke and Pisinger (2006). Let P be the set of pickup nodes and D the set of delivery nodes. Each request r in the portfolio R_i with load l_r must be transported from its pickup location to delivery location. A vehicle fleet K is available for the fulfillment of requests. Each vehicle $k \in K$ has a limited capacity and has to start and end its tour at its depot. Denote the set of all depot nodes as O, the node set of the graph is $V = P \cup D \cup O$. For each edge of the graph $(u, v) \in A = V \times V$, a distance $d_{uv} \geq 0$ is given. The service at each node $u \in V$ must be started within a time window. Each vehicle $k \in K$ has a fixed cost α_k and a variable cost rate β_k for each distance unit. The binary decision variable x_{uvk}, $u, v \in V$, $k \in K$, is one if and only if vehicle k travels from node u to node v. The objective function is:

$$\min \sum_{k \in K} \alpha_k + \sum_{k \in K} \sum_{(u,v) \in A} \beta_k d_{uv} x_{uvk} \tag{1}$$

This objective function minimizes the total costs, which are composed of the fixed costs and travel costs. Denote $\mathrm{FC} = \sum_{k \in K} \alpha_k$ as the fixed costs and $\mathrm{VC} = \sum_{k \in K} \sum_{(u,v) \in A} \beta_k d_{uv} x_{uvk}$ as the variable costs, then (1) can be written as

$$\min \mathrm{FC} + \mathrm{VC} \tag{2}$$

The total execution costs of all freight carriers in the isolated planning are $\mathrm{TC}_{IP} = \sum_{i=1}^{m} C_i$. Consequently, TC_{IP} represents the upper bound for a CTP solution to be accepted. In centralized planning, a multi-depot PDPTW has to be solved for the entire request set $R = \cup_{i=1}^{m} R_i$. The total costs of the resulting routing plan Π for the entire coalition is denoted as TC_{CP}, which is the lower bound for the CTP scenario.

In the CTP scenario, the request portfolio R_i of carrier i is completely offered for exchange. R_i can be divided into two parts. The first part is the set of requests $R_i^0 \subseteq R_i$ that have been offered but not transferred to other partners. The transferred requests constitute the set $R_i^- = R_i \backslash R_i^0$. The new request portfolio after the exchange is $R_i' = R_i^0 \cup R_i^+$, where R_i^+ is the set of requests acquired from other partners that carrier i has won. The execution costs for the new request portfolio R_i' according to a plan Π_i' are given by C_i'. The CTP can be modeled as the following optimization problem

$$\min\ \mathrm{TC}_{CTP} = \sum_{i=1}^{m} C_i' \tag{3}$$

subject to:

$$R_i' \cap R_j' = \varnothing \quad \forall i, j = 1, \ldots, m, i \neq j \tag{4}$$

$$\bigcup_{i=1}^{m} R_i^- = \bigcup_{i=1}^{m} R_i^+ \tag{5}$$

The objective function (3) minimizes the total fulfillment costs of the entire coalitions. Restriction (4) ensures that each request is shifted to exactly one other member. Equation (5) ensures that all transferred requests are acquired by coalition partners.

4 A route-based request exchange mechanism

Cost-saving potentials are embedded in the complementarities of two or more LTL requests and are exploited by combining them into bundles. In this section, a route-based request exchange mechanism is presented for CTP within a GS of independent freight carriers. The main motivations for our design are to ensure that exchanged bundles can be exactly evaluated, to guarantee the protection of private information, and to deal with the difficulties caused by introducing capacity restrictions. Our approach aims to find out CTP solutions that will increase the coalition's total profit and thus it will be possible by means of profit sharing that any participant's individual situation will definitely not worsen. We do not consider specific strategies for profit sharing, since this topic goes beyond the scope of this research.

Figure 3 gives an overview of the entire process of the route-based request exchange mechanism. In the preprocessing phase, participating carriers propose their requests that can be exchanged with other partners in a common pool. Moreover, a transfer price

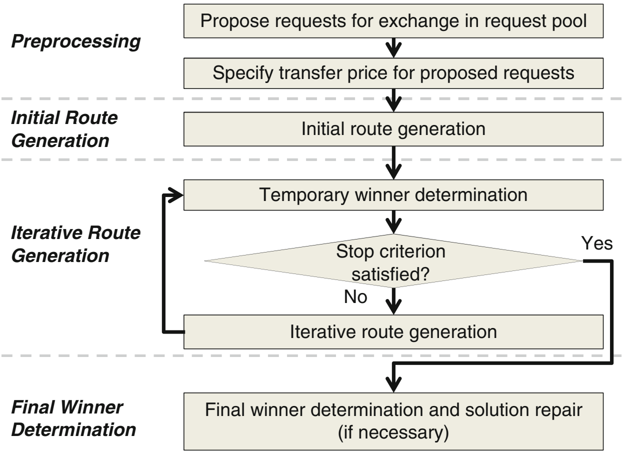

Fig. 3 Overview of the route-based request exchange mechanism for CTP

has to be specified and will be paid to the agent if someone else in the coalition intends to execute these requests. After that, all partners generate and submit some candidate vehicle routes to initiate the iterative route generation process. For each candidate route, the ask price has to be specified based on the fulfillment costs. In the iterative route generation phase, the problem of temporary winner determination modeled as an SPP is solved aiming to minimize the total fulfillment costs of all requests. The dual values related to the requests are then obtained by the agent while solving a linear relaxation of the SPP and these values are given to the carriers, who can generate and submit new candidate vehicle routes iteratively until a certain stop criterion is satisfied. In the next step, the final winning routes are chosen by a final winner determination. For the execution of the winning routes, the ask prices will be paid to the carriers by the agent. The difference between the total transfer prices paid to the agent and the total ask prices of winning routes paid by the agent will be determined as joint benefits of the coalition.

4.1 Preprocessing

In this paper, we do not discuss the decision problem which is related to the selection of requests to be offered for exchange. Instead, we assume that all partners $i = 1, \dots, m$, offer their entire request portfolios R_i for exchange. Alternatively, it can be assumed that all partners have identified the request portfolios R_i, which they want to offer for exchange, in advance on the basis of a preliminary vehicle routing. In this case, $R_i^* \supseteq R_i$ represents the entire set of requests acquired by carrier i from his customers. In case of $R_i \subset R_i^*$, it is important to postulate that, with respect to the preliminary vehicle routing, none of the requests $r \in R_i$ is combined in a tour with any request $r' \in R_i^* \setminus R_i$. This means that within a preliminary planning each partner identifies very efficient routes which he wants to fulfill without request exchange and offers all other requests that are not contained in these routes for exchange.

As a consequence, the problem collaborating partners have to solve in the preprocessing phase is to specify the transfer prices for their own request sets R_i. It seems to be desirable that the carriers can specify the transfer price for each single request $r \in R_i$. However, to specify the exact cost as its transfer price for each single LTL request which is fulfilled together with many other ones in a common route is impossible. We thus design a mechanism which only needs an aggregated transfer price for the whole request portfolio R_i proposed by participant i. In order to determine the transfer price, each participant just needs to solve a PDPTW for the own requests he offers for exchange. For the fulfillment of his own initial request portfolio R_i within the coalition, participant i will not be willing to pay more than the transfer price C_i. The transfer prices are known but kept sealed by the agent. The sum of transfer prices of the request portfolios of all partners are the total fulfillment costs of the isolated planning TC_{IP}. Based on the transfer prices of all partners, the GS will accept only those CTP solutions with $\mathrm{TC}_{CTP} \leq \mathrm{TC}_{IP}$. As long as a CTP solution is accepted, the joint profits can be calculated as $\mathrm{TC}_{IP} - \mathrm{TC}_{CTP}$.

An important piece of information that must be transferred to the agent is the maximal number of routes that a participant can be assigned; i.e., the number of vehicles in the participant's own fleet available for the CTP. The agent can therefore make sure in the determination of winning routes that no partner will be assigned more routes than his fleet capacity allows.

After all partners have proposed their sets of requests, the request pool $R = \cup_{i=1}^{m} R_i$ is complete and the route generation phase starts.

4.2 Route generation process

During the route generation process, carriers face two important questions: which requests in the pool R should be chosen for their own vehicles available for CTP, and how these requests should be bundled into candidate vehicle routes. Theoretically, carriers can consider all vehicle routes as long as they are feasible. For common problem sizes, this is not practical due to the very large number of possible routes. Moreover, the efficiency of a participant's plan Π_i' will be strongly diluted if some requests are covered by several of his winning routes but can be actually executed in only one route. Thus, instead of generating single routes, entire PDPTW solutions are generated to use the complementarities of these routes. By solving the PDPTW heuristically, a set of good but different solutions can be obtained at a time. The routes in the PDPTW solutions are then submitted for winner determination.

4.2.1 Initial route generation

Since each freight carrier can fulfill only a part of the requests in the pool R, he has to select the requests he wants to serve and has to create candidate vehicle routes for the fulfillment of the selected requests. The problem to be solved is thus a combined request selection and routing problem (see e.g., Butt and Ryan 1999 or Feillet et al. 2005).

At the beginning of the route generation process, carriers only know which requests are in the pool. Without knowing any payments for requests, they have to generate efficient routes with costs as low as possible. Their planning goals in this *initial route generation* step can thus be specified as firstly to get enough requests for their fleets, and secondly to generate efficient routes. The first goal strives to increase the use of the own fleet, while the second one makes their candidate routes competitive and helps exhausting more cost-saving potentials. Accordingly, for the combined request selection and routing problem in this step, the primary objective is to include as many requests as possible in the routes and the secondary objective is to reduce the routes' costs. We denote this combined problem of request selection and PDPTW as RSPDPTW1. In order to define this problem, a "penalty cost" γ_r, $r \in R$ is introduced, which will be charged if request r is not planned in any route. A binary variable z_r, $r \in R$, representing whether a request is part of a route or not, is added to the model. If request r is not planned in any route, z_r will be one. The objective function (2) can be extended as follows for RSPDPTW1:

$$\min \mathrm{FC} + \mathrm{VC} + \sum_{r \in P} z_r \gamma_r \qquad (6)$$

Requests with higher penalty costs will be preferred to be integrated in routes of the CTP compared to those having less penalty costs. An extremely high value will guarantee that the corresponding request will be planned in some route, as long as the capacity restriction holds.

After this problem has been solved in a heuristic manner, a set of good but different solutions are generated. All vehicle routes in these solutions are submitted for the winner determination with their costs as ask prices. For each route, the ask price can be formally defined as:

$$p_k = \alpha_k + \sum_{(u,v)\in A} \beta_k d_{uv} x_{uvk} \tag{7}$$

4.2.2 *Temporary winner determination*

When no carrier wants to submit any further candidate routes, the agent temporarily solves the current winner determination problem (WDP) to provide useful information for the *iterative route generation* step (see Sect. 4.2.3). Suppose that n requests are offered for exchange, $R = \{1, \ldots, n\}$, and each carrier i has submitted b_i candidate routes. We add a fictive route for each single request in R with a very large ask price $p_{\max}$ to make sure that the WDP always has feasible solutions. The total number of candidate routes is $b = \sum_{i=1}^{m} b_i + n$. Let $a_{rj} = 1$ indicate that request $r \in R$ is held by route j and $a_{rj} = 0$ otherwise. The ask price for route j is p_j, $j = 1, \ldots, b$. The WDP can be modeled as an SPP by introducing a binary variable y_j, $j = 1, \ldots, b$, where $y_j = 1$ indicates that route j is chosen as a winning route.

$$\min \ \mathrm{TC}_{CTP} = \sum_{j=1}^{b} y_j p_j \tag{8}$$

subject to:

$$\sum_{j=1}^{b} a_{rj} y_j = 1 \qquad \forall r = 1, \ldots, n \tag{9}$$

$$y_j \in \{0, 1\} \quad \forall j = 1, \ldots, b \tag{10}$$

Since we want to consider the capacity restrictions of freight carriers, this model has to be extended. Let $f_{ij} = 1$ if a route j is submitted by freight carrier i and $f_{ij} = 0$ otherwise. Participant i has k_i vehicles in his fleet. We add the following constraint to the above model.

$$\sum_{j=1}^{b} f_{ij} y_j \leq k_i \quad \forall i = 1, \ldots, m \tag{11}$$

The objective function (8) together with restrictions (9)–(11) constitute the SPP-based model of the WDP. Denote this model as WDP-SP.

A linear relaxation of the WDP-SP is given by replacing (10) with

$$y_j \geq 0 \quad \forall j = 1, \ldots, b \tag{12}$$

Denote the relaxed model (8), (9), (11) and (12) as WDP-LP. Then, the dual values of constraint (9) can be used for generating new candidate routes. The route generation problem is to build new candidate routes with negative reduced costs $\bar{c_j}$, which can be calculated as follows for a variable y_j,

$$\bar{c_j} = p_j - \sum_{r=1}^{n} \pi_r a_{rj} - \sum_{i=n+1}^{n+m} \sigma_i f_{ij} \tag{13}$$

where π and σ represents the dual variables corresponding to the constraints (9) and (11), respectively. The objective value of WDP-LP can then be reduced by letting these new routes with negative reduced costs enter the basis until no route with $\bar{c_j} < 0$ can be found. The dual values π_r of the requests, $r = 1, \ldots, n$, are read by the agent and sent back to carriers in a revised form π'_r, which can be determined by introducing a predefined minimal value $\pi_{\text{min}} \geq 0$ as:

$$\pi'_r = \begin{cases} \pi_{\text{min}} & \text{if} \quad \pi_r < \pi_{\text{min}} \\ \pi_r & \text{if} \quad \pi_r \geq \pi_{\text{min}} \end{cases}$$

4.2.3 Iterative route generation

Consider the meaning of the dual values π'_r, $r = 1, \ldots, n$, for the carriers. If route j is generated by a specific carrier i, we have $f_{ij} = 1$ and $f_{hj} = 0$, $h = 1, \ldots, m$, $h \neq i$. Thus, (13) reduces for a particular carrier to:

$$\bar{c_j} = p_j - \sum_{r=1}^{n} \pi'_r a_{rj} - \sigma_i \tag{14}$$

To find a route with $\bar{c_j} < 0$ for a particular carrier i is equivalent to find a route with $-\bar{c_j} = \sum_{r=1}^{n} \pi'_r a_{rj} + \sigma_i - p_j > 0$. Note that p_j is the ask price, which is the cost of a route. The revised dual values π'_r can be seen as a "fictive payment" for the fulfillment of a request r and the first term is then the total earning of this route. The second term σ_i can be regarded as the fixed costs for the vehicle, because σ_i is the dual variable for constraint (11) and it will always be non-positive as long as the dual problem of WDP-LP is solvable. This interpretation helps to understand how this new route generation problem can be converted into a routing problem. As a result, the above task can then be interpreted as finding out a vehicle route with positive revenue.

Normally, this task is done by solving an optimization problem with the objective of maximizing $-\bar{c_j}$. If a feasible solution to this problem with non-positive objective value is found, a new route is generated. In this paper, however, we follow a new idea to solve the route generation problem in this step by using two strategies for the searching process. First, instead of looking for one route, several routes are simultaneously generated. Specifically, this means that k_i routes are generated at once by carrier i following the objective function:

$$\max \sum_{j=1}^{k_i} \sum_{r=1}^{n} \pi'_r a_{rj} + k_i \sigma_i - \sum_{j=1}^{k_i} p_j \tag{15}$$

Hence the new route generation problem is to solve a request selection and routing problem in order to maximize the resulting revenue, which is calculated by subtracting the route costs from the "fictive payments" π'_r for the planned requests in the routes. The second strategy is to introduce $\pi_{\min}$ to give requests with small or even negative dual values the chance to be inserted into routes, only of course if the insertion causes very little costs. These two strategies help to find not only "good" routes that will improve the WDP-LP objective values, but also routes that are complementary to those good ones.

We denote this route generation problem as RSPDPTW2. The objective function (15) can be formulated in a way that RSPDPTW2 is modified to a revenue maximization problem. The first term of (15), $\sum_{j=1}^{k_i} \sum_{r=1}^{n} \pi'_r a_{rj}$, calculates the total "fictive payments" for all requests planned in routes and can thus be substituted by $\sum_{r \in R} \pi'_r (1 - z_r)$. As a result, the objective function of RSPDPTW2 can be redefined as

$$\max \sum_{r \in R} \pi'_r (1 - z_r) - \mathrm{VC} - \mathrm{FC} + k_i \sigma_i \tag{16}$$

This objective function (16) can be reformulated as a cost minimization function like in RSPDPTW1 by setting $\gamma_r = \pi'_r, \forall r \in R$. We have

$$\begin{aligned}
&\max \sum_{r \in R} \pi'_r (1 - z_r) - \mathrm{VC} - \mathrm{FC} + k_i \sigma_i \\
&= \sum_{r \in R} \gamma_r (1 - z_r) - \mathrm{VC} - \mathrm{FC} + k_i \sigma_i \\
&= \sum_{r \in R} \gamma_r - \sum_{r \in R} z_r \gamma_r - \mathrm{VC} - \mathrm{FC} + k_i \sigma_i \\
&\Leftrightarrow \min \mathrm{VC} + \mathrm{FC} - k_i \sigma_i + \sum_{r \in R} z_r \gamma_r - \sum_{r \in R} \gamma_r \\
&= \mathrm{VC} + \mathrm{FC}' + \sum_{r \in R} z_r \gamma_r
\end{aligned}$$

where $\mathrm{FC}' = \mathrm{FC} - k_i \sigma_i - \sum_{r \in R} \gamma_r$. Now we can use the same heuristic to solve both, RSPDPTW1 and RSPDPTW2. This heuristic will be presented in Sect. 5.2. The newly submitted routes are added to the existing candidate route set. The Steps *temporary winner determination* and *iterative route generation* are repeated until some stop criteria are satisfied. The route generation phase is then concluded. Please note that although this phase may have some iterations, the whole process has only one round. This means that the final winning routes will only be decided once in the following Step *final winner determination*.

4.3 Final winner determination

In this phase, the WDP is modeled as a set covering problem (SCP) through substituting the constraint (9) by

$$\sum_{j=1}^{b} a_{rj} y_j \geq 1 \quad \forall r = 1, \ldots, n \tag{17}$$

We denote this problem, defined by (8), (10), (11), and (17), as WDP-SC. Additionally, to make sure that the WDP-SC always has feasible solutions, a fictive route containing a single request $r \in R$ with the ask price $p_{\max}$ is added to the set of candidate routes for all requests by the agent.

The reason for choosing the SCP-based formulation for the WDP instead of further using the WDP-LP is to minimize the efforts needed to get a feasible solution to the WDP-SP if the solutions of WDP-LP and WDP-SC are not feasible to WDP-SP. In WDP-LP, since the integrity of the binary variable y_j has been relaxed, a WDP-LP solution will be infeasible to WDP-SP because some variables y_j have fractional values. In order to get a feasible integer solution, a Branch-and-Bound (B&B) search process has to be applied. Such B&B processes may put great demands on the computational efforts as well as on the communications between the carriers and the agent, which is undesirable in the collaborative planning context. On the contrary, as the relaxation of WDP-SC allows that each request is assigned to more than one winning route, a WDP-SC solution can be infeasible to WDP-SP. Such infeasible solutions can easily be repaired to feasible WDP-SP solutions through removing all multi-assigned requests from all but one route. We use a simple heuristic to repair an infeasible WDP-SP solution obtained using WDP-SC in this way. Hoping to minimize the damage of the synergy effects embedded in the routes, we give the multi-assigned requests to those partners who have won most of them. Then, the agent asks each carrier for the total ask price of the entire set of requests he has finally won after the exchange and repair procedure, which is the overall costs of the carrier's new routing plan. Finally, the agent actualizes the result of the WDP.

Besides the requests that are successfully assigned in the winning routes, some requests may be left unassigned. Eventually, these requests are likely to be outsourced to external common carriers. In this case, the agent will ask the prices for outsourcing and perform the subcontracting if the CTP solution is accepted by the GS. The total costs of the WDP-SP solution, including both the winning routes' ask prices and the possible costs for subcontracting, will be compared with the isolated planning results. The WDP-SP solution will only be accepted if positive joint benefits can be realized.

5 Computational experiments

The performance of the route-based request exchange mechanism for CTP described in Sect. 4 will now be evaluated by means of computational experiments. Since we have introduced a new CTP scenario with LTL requests of a PDPTW, we need to generate test instances for that scenario. The method used to generate new CTP instances will be introduced first. Next, the route generator that solves both, the RSPDPTW1 and RSPDPTW2, will be presented. CTP results obtained by applying our mechanism are presented and discussed at the end of this section.

5.1 Test instance generation

CTP test instances are generated by combining different PDPTW benchmark test instances generated by Li and Lim (2001), while each of them represents the request set of an individual participant of the GS. Instances with the same characteristics (`C`, `R`, or `RC`) and size (100-cases) are combined together into single CTP test instances. Before a PDPTW instance is inserted into a CTP instance, coordinates of all nodes of this PDPTW instance have to be adjusted with the same amount $(\Delta X, \Delta Y)$ in order to correspond to the locations of carriers in different regions. The number of vehicles in the own fleets is given as the number of used vehicles in the best-known solutions obtained from five heuristics: the heuristic by Li and Lim (2001), the heuristic by Bent and van Hentenryck (2003), the heuristic by Ropke and Pisinger (2006), and two commercial heuristics including the one developed by SINTEF and the other by TetraSoft A/S. Data sets of these PDPTW instances and detailed results can be found on a web page maintained by SINTEF (http://www.sintef.no/Projectweb/TOP/PDPTW/Li--Lim-benchmark/).

For simplicity, all vehicles are assumed to have the same capacity given in the original data and the cost structure is fixed by setting the variable cost rate for each distance unit $\beta_k = 1$ for each carrier i and each vehicle $k \in K_i$. We further assume that all vehicles have the same fixed costs, so that the fixed cost term can be ignored during the planning. Thus, we can set the fixed cost α_k to zero and only focus on the variable costs of the routes. This offers the possibility to directly use the benchmark solutions to determine the costs for the isolated planning scenario and to minimize the deviation from the optimal solutions caused by applying heuristics. The detailed information about the generation of our test instances can be found in Table 3 in the Appendix. In total, 24 CTP instances, containing 2–5 carriers each, have been generated using the 100-case PDPTW instances in the sets `LC1`, `LR1`, and `LRC1`. We have not used the sets `LC2`, `LR2` and `LRC2`, because the gap between isolated and centralized planning is very small in these instances. The extreme long planning horizon of sets `LC2`, `LR2` and `LRC2` permitting much more customers to be serviced by the same vehicle (Solomon 1987) makes it possible to get equivalent good solutions in both isolated and centralized planning scenarios.

5.2 Route generator

In order to generate routes and to solve the routing problems for the reference scenarios, we have developed a large neighborhood search (LNS) heuristic based on the adaptive LNS (ALNS) proposed by Ropke and Pisinger (2006), which is one of the most competitive algorithms for solving the generalized PDPTW (Parragh et al. 2008).

We have carried out two modifications in our implementation to make this heuristic suitable for the route generation. Our implementation is written in C++.

The ALNS heuristic developed by Ropke and Pisinger (2006) is constructed using a simulated annealing (SA) framework. In each iteration the current solution is firstly destroyed by using one of the three removal-heuristics: worst removal, random removal and Shaw removal, which remove a number of requests from the vehicle routes. In the next step, one insertion heuristic is chosen and used to reinsert the removed requests into vehicle routes. There are two types of insertion heuristics that can be used, i.e., the basic greedy heuristic and the regret-heuristics (see Ropke and Pisinger 2006; Potvin and Rousseau 1993 for more details). The probability of a removal/insertion heuristic being chosen is adapted during the search process.

The first modification concerns the usage of the insertion heuristics. The purpose of this modification is to get more promising solutions and in turn more good candidate routes by intensifying the search in each iteration of the SA process. This has been done through conducting a more thorough search by applying all insertion operators to the current solution after a removal heuristic has been executed. While the best solution is chosen as candidate solution for the next iteration, all other solutions are also recorded for route generation. Since we do not apply the adaptive mechanism, we set the probabilities for executing the three removal-heuristics: worst removal, random removal and Shaw removal to 0.2, 0.4, and 0.4, respectively.

Since this modification may make the heuristic to be more myopic in the search process, we have tested our LNS heuristic to verify the modification. We ran the LNS heuristic on each of the 100-case and 200-case instances ten times by giving γ_r large values. The heuristic has the same objectives as the majority of other heuristics for solving the PDPTW in the literature: firstly to minimize the number of vehicles and secondly to minimize the total distances. All of our best solutions have the same numbers of vehicles as the best-known ones reported by SINTEF. With respect to the total distances, we have found the same best-known solutions for 53 of 56 instances of the 100-cases and for 29 of 60 instances of the 200-cases, respectively. The average deviation between the best-known solutions and our best solutions of all test instances in the 100-cases is 0.08 %. For the 200-cases it is 1.14 %. It implies that our modification performs only slightly worse than the original ALNS. However, for the two test instances `LR2_2_10` and `LRC2_2_3`, we have found better solutions than those published by SINTEF. We improved the results for `LR2_2_10` with 3 vehicles from 3323.37 to 3316.39 and for `LRC2_2_3` with 4 vehicles from 2938.28 to 2934.98. The results indicate that the modified heuristic can offer solutions to the PDPTW test instances of high quality that is comparable to the original ALNS proposed by Ropke and Pisinger (2006) while it increases the number of solutions considered for route generation. Our heuristic for the PDPTW constitutes the basis for the development of the CTP approach. Later on in this paper, the LNS heuristic is used for the generation of benchmarks by providing very good sub-optimal solutions for centralized planning. These sub-optimal solutions are lower estimations for CTP and are used for the performance evaluation of our CTP approach.

The second modification enables our LNS heuristic to solve RSPDPTW1 and RSPDPTW2 for route generation. The insertion heuristics inserts requests into vehicle routes based on the insertion cost Δc_{rk}, which is defined as the increment of route costs after a request r has been inserted into a route k at the best possible position. In the original ALNS for the PDPTW, the algorithm inserts a request into a vehicle route whenever it is possible because all requests must be planned in vehicle routes. In our heuristic however, the difference of $\pi'_r - \Delta c_{rk} = \gamma'_r - \Delta c_{rk}$ is calculated. On one hand, requests with $\gamma'_r - \Delta c_{rk} > 0$ are automatically considered as candidates for insertion into vehicle routes because compared with the penalty cost this insertion is cheaper. On the other hand, those requests that have negative difference values with $\gamma'_r - \Delta c_{rk} < 0$ are also considered for insertion if $\Delta c_{rk} - \gamma'_r \leq \zeta T_{it}$ holds, where ζ is a threshold parameter and T_{it} is the temperature in iteration it. At the beginning of the search process, the temperature of the SA process T_{it} is large and the heuristic tries to insert all requests into vehicle routes. The result is similar to PDPTW solutions in which the vehicle routes are generally quite efficient. When T_{it} becomes smaller and smaller, the heuristic becomes more selective and the requests can only be (re-)inserted into vehicle routes if the insertion will reduce the overall objective value, i.e., the difference value $\gamma'_r - \Delta c_{rk}$ is strictly positive.

During the route generation process, up to θ of the best solutions found in the search process are recorded. Routes in these solutions are submitted. For RSPDPTW1 and RSPDPTW2, the objective is only to minimize the costs or to maximize the revenues, respectively, regardless of how many vehicles are utilized.

5.3 Computational results

As upper estimations for our tests, we use the best-known values from literature to calculate the total costs TC_{IP} of the isolated planning scenario. To calculate a lower estimation for the TC_{CP} (centralized planning), we solve the multi-depot PDPTW using the above-mentioned modified heuristic of Ropke and Pisinger (2006). For each instance, the multi-depot PDPTW is solved three times and the algorithm runs $\Psi = 15{,}000$ iterations each time. The best results of the three runs are given in the fifth column in Table 1. For CTP, carriers repeatedly solve the RSPDPTW1 and RSPDPTW2 using the same algorithm during the route generation process. Tuning experiments resulted in the following parameter setting, which offers a fair trade-off between time and quality. Each time, the algorithm runs only $\Psi = 5{,}000$ iterations and the vehicle routes in up to $\theta = 300$ of the best solutions found in these 5,000 iterations are submitted. In the *initial route generation* step, the penalty cost γ_r is set to 400. The minimal revised dual value for requests $\pi_{\min}$ is set to 10. For the WDP, the ask price for the fictive routes $p_{\max}$ is set to 400. We only execute one trial on each instance for the collaborative planning. The route generation process is stopped after 10 iterations or when the improvement of the objective value of the WDP-LP is less then β percent. For our tests, β is set to 0.1, 0.2, 0.5, and 1.0 % for instances with 2, 3, 4 and 5 freight carriers, respectively.

The results are shown in Table 1. The number of freight carriers m is given in the second column and the number of all requests n in the third column. The absolute cost-saving potentials $\Delta\mathrm{TC}_1 = \mathrm{TC}_{IP} - \mathrm{TC}_{CP}$ and the relative cost-saving potentials $\phi_1 = 100 \cdot \Delta\mathrm{TC}_1/\mathrm{TC}_{IP}$ (%) are shown in the sixth and seventh column. Columns eight to ten give the results of the CTP. The columns for $\Delta\mathrm{TC}_2 = \mathrm{TC}_{IP} - \mathrm{TC}_{CTP}$ and

Table 1 Results of planning

Instance	m	n	Isolated planning	Centralized planning			Collaborative planning						
			TC$_{IP}$	TC$_{CP}$	ΔTC$_1$	ϕ_1 (%)	TC$_{CTP}$	ΔTC$_2$	ϕ_2 (%)	η (%)	$\#it_{RG}$	$\overline{\tau}_{RG}$ (min)	τ_{SC} (s)
C101	2	105	1,864.29	1,691.63	172.66	9.26	1,699.08	165.21	8.86	95.68	7	0.80	0.64
C102	2	106	1,655.38	1,539.82	115.56	6.98	1,539.82	115.56	6.98	100.00	6	0.75	0.02
C103	3	159	2,658.48	2,391.34	267.14	10.05	2,414.99	234.49	9.16	91.15	8	1.56	3.40
C104	3	159	2,517.89	2,194.32	323.57	12.85	2,198.10	319.79	12.70	98.83	9	1.86	0.69
C105	4	212	3,518.49	3,041.51	476.98	13.56	3,027.86	490.63	13.94	102.86	7	3.11	11.14
C106	4	211	3,519.67	2,867.63	652.04	18.53	2,882.58	637.09	18.10	97.71	7	3.04	6.21
C107	5	264	4,348.61	3,586.74	761.87	17.52	3,579.69	768.92	17.68	100.93	7	3.46	173.74
C108	5	264	4,348.61	3,601.71	746.90	17.18	3,596.64	751.97	17.29	100.68	5	3.48	0.95
Avg.C	–	–	–	–	–	13.24	–	–	13.09	98.48	7.00	–	–
R101	2	104	2,452.03	2,269.32	182.71	7.45	2,263.21	188.82	7.70	103.35	6	0.68	0.36
R102	2	104	2,363.93	2,311.77	52.15	2.21	2,311.98	51.95	2.20	99.60	5	0.63	0.53
R103	3	160	3,600.24	3,444.36	155.88	4.33	3,394.24	206.00	5.72	132.15	7	1.22	5.29
R104	3	154	3,239.63	3,041.63	198.00	6.11	3,014.98	224.65	6.93	113.46	7	1.35	13.67
R105	4	208	4,434.32	3,960.58	473.74	10.68	3,906.01	528.31	11.91	111.52	6	2.29	140.54
R106	4	215	5,624.38	5,112.16†	512.22	9.11	5,038.12†	586.26	10.42	114.45	6	2.71	5.43
R107	5	265	6,139.11	5,211.12†	927.99	15.12	5,031.74‡	1107.37	18.04	119.42	5	3.30	429.75
R108	5	262	5,843.75	5,332.08	511.67	8.76	5,186.87†	656.88	11.24	128.38	6	2.79	72.26
Avg.R	–	–	–	–	–	7.97	–	–	9.27	115.29	6.00	–	–
RC101	2	106	2,488.89	2,378.99	109.90	4.42	2,386.78	102.11	4.10	92.91	6	0.75	0.48
RC102	2	107	2,867.77	2,690.49	177.28	6.18	2,696.04	171.73	5.99	96.87	5	0.63	0.34
RC103	3	160	3,945.21	3,544.73	400.48	10.15	3,511.99	433.22	10.98	108.18	6	1.32	3.06
RC104	3	161	4,190.75	3,693.64	497.11	11.86	3,650.29	540.46	12.90	108.72	8	1.48	0.22
RC105	4	211	5,345.12	4,680.19†	664.93	12.44	4,539.76	805.36	15.07	121.12	6	1.91	17.42
RC106	4	213	5,341.35	4,881.84	459.51	8.60	4,777.83	563.52	10.55	122.63	6	1.86	86.22
RC107	5	265	6,639.51	5,800.29	839.22	12.64	5,596.27	1,043.24	15.71	124.31	5	2.56	657.59
RC108	5	266	7,393.38	6,237.40	1155.98	15.64	6,100.68†	1,292.70	17.48	111.83	6	2.88	25.05
Avg.RC	–	–	–	–	–	10.24	–	–	11.60	110.82	6.00	–	–
Avg.All	–	–	–	–	–	10.46	–	–	11.32	108.20	6.33	–	–

† Solutions with one vehicle less used compared with the isolated planning

‡ Solutions with two vehicles less used compared with the isolated planning

Table 2 Efficiency and computational effort for different instance sizes

m	$\overline{\phi}_1$ (%)	$\overline{\phi}_2$ (%)	$\overline{\eta}$ (%)	$\overline{\#it}_{RG}$	$\bar{\bar{\tau}}_{RG}$ (min)	$\bar{\tau}_{SC}$ (s)
2	6.08	5.97	98.07	5.83	0.71	0.40
3	9.23	9.73	108.75	7.50	1.47	4.39
4	11.65	13.33	111.72	6.33	2.49	44.49
5	14.47	16.10	114.26	5.67	3.08	226.56

$\phi_2 = 100 \cdot \Delta \mathrm{TC}_2/\mathrm{TC}_{IP}$ (%) show the absolute and relative cost reduction compared to the isolated planning. The efficiency parameter $\eta = 100 \cdot \Delta \mathrm{TC}_2/\Delta \mathrm{TC}_1$ (%) shows the realized percentage of cost-saving potentials and thus how efficient the request exchange mechanism is. Note that the values TC_{CP} for centralized planning are high-quality sub-optimal solutions generated by using the LNS heuristic which has been introduced and evaluated in Sect. 5.2. They are not necessarily identical to the optimal solution of centralized planning. Values for $\#it_{RG}$ are the numbers of route generation iterations and the values for $\overline{\tau}_{RG}$ are the average time used by one carrier to solve the RSPDPTW1 and RSPDPTW2 once. The evaluation of the fulfillment costs of the routing plan for the entire request portfolio in the *final winner determination* step is not counted in $\#it_{RG}$. All route generation problems are solved on an Intel Core i7 PC (8 cores à 3.2 GHz). Finally, τ_{SC} is the time elapsed to solve the WDP-SC using IBM CPLEX 12.2 on an Intel Core i5 PC (4 cores à 3.33 GHz). Both PCs run Windows operation systems. We do not report the time used to solve WDP-LP, since it can be solved very quickly. The longest time is only 6.3 s for 5 carriers with totally 265 requests, 60 vehicles and 17,954 routes. No request has to be subcontracted after the exchange.

5.4 Discussion of results

The results indicate that the route-based request exchange mechanism works very well for CTP. For 17 of the 24 instances, we have found solutions that are equal with or better than those obtained by using the LNS heuristic for centralized planning. However, it must be mentioned that the decentralized approach makes more demands on computational time than the LNS. Considering the solution quality, the decentralized planning through the CA has found obviously better solutions than the LNS heuristic particularly for the large instances in Sets `R` and `RC`. It seems that, especially for the instances with more participants, the CTP results can be further improved by reducing β and performing more iterations of route generation $\#it_{RG}$ and/or by increasing θ to submit more candidate routes in each iteration. Our test settings show a stable performance with acceptable computational efforts for the collaborative planning scenario.

A summarized comparison of efficiency and computational effort for different instance sizes is shown in Table 2. It is obvious that, with increasing number of participants in a coalition, the cost-saving potentials also rise, but it becomes increasingly difficult for heuristic approaches to solve the problem centrally. Instead, the CTP appears to be a more preferable solution strategy. The success of our mechanism is based on the ability of the route generator to find more local optima by intensifying the search process (see Sect. 5.2), without necessarily having found a global optimum. CTP can provide satisfactory good solutions even when the number of iterations (5,000) running the heuristic for RSPDPTW1 and RSPDPTW2 is relatively small compared with the number of iterations running the heuristic in the centralized planning (15,000). Meanwhile, the average time used for route generation $\bar{\bar{\tau}}_{RG}$ as well as the average time used for the WDP-SC $\bar{\tau}_{SC}$ also increases. However, it is surprising that the average number of route generation iterations $\overline{\#it}_{RG}$ does not significantly change, although the stopping criterion has been changed slightly.

Another important observation is that τ_{RG} reduces significantly (up to 40 %) in the late phase compared with the first iterations of the route generation process, because the route generator can be very well guided by the feedback information about the dual values. Requests with extremely low π'_r values will just be excluded from the consideration and carriers can efficiently generate promising routes even while ignoring a part of the requests in the pool.

6 Conclusion and future work

In order to increase the operational efficiency, SMC can build up GSs and apply CTP techniques. Members of such GSs can profit from the collaboration with partners without losing their autonomy. Through exchange of transportation requests, vehicle routes that are more efficient can be built and the total execution costs for the coalition can be reduced. In this paper, the CTP problem of independent freight carriers has been investigated. The collaborative scenario introduced and investigated here represents the most general one in the literature in three aspects. First, the underlying routing problem is the PDPTW with LTL requests. Secondly, the impacts of capacity restrictions on CTP have been dealt with explicitly. Finally, the degree of information exposure is low and decision-making competences within the GS remain distributed.

A route-based request exchange mechanism is proposed and evaluated using some newly generated CTP test instances. The results show that our new mechanism can implement the cost-saving potentials embedded in the CTP to a great extent. For more than two-thirds of the instances, it even outperforms the LNS heuristic in terms of the total fulfillment costs. However, more computational efforts are required by the CTP approach. Although the comparison shown in Table 1 seems to be a comparison of two heuristic approaches for the multi-depot PDPTW, it is merely meant to be considered as a measurement of the efficiency of our request exchange mechanism for CTP, since clearly, using full transparency of centralized planning can in general lead to more powerful solution approaches than decentralized approaches which keep the autonomy of the planning partners. The major difference between them is that the route-based request exchange mechanism is tailored for decentralized decision-making but the LNS heuristic is not. Apart from considering collaborative planning problems, the computational experiments performed for the CTP scenarios demonstrate that the solution method proposed in this paper also yields an alternative and competitive approach for generating high-quality solutions for large-scale (multi-depot) PDPTW instances.

We only study the scenario where freight carriers have homogeneous fleets, but the proposed mechanism can be easily extended for heterogeneous fleets. The only change is that each carrier has to specify the capacity for each type of vehicle in his fleet. In the experimental settings investigated in this paper we assume that before the exchange of requests, all requests of any carrier can be fulfilled by the fleet of this carrier without any need of subcontracting. This assumption can easily be relaxed by assuming that the decision upon subcontracting has been made in advance before the exchange process starts. Considering simultaneous subcontracting and request exchange among coalition partners, however, is a complicated task which will be a topic of future research. A crucial prerequisite for the high efficiency of our approach is that all carriers offer all their requests for exchange. This is unrealistic for coalition members who are related in a partnership as it is usually implemented in carrier coalitions. According to our observations in practice the above prerequisite can be fulfilled in a GS built by profit centers of a unique enterprise. Nevertheless, the investigation on the route-based exchange mechanism is valuable to show the potential of this approach and we are convinced that route-based request exchange mechanisms constitute a promising technique for CTP for any type of carrier coalition. In case that not all requests are offered for exchange, the question arises which ones should be retained and which ones should be offered. This is a difficult and more or less unsolved problem which will be a matter of future research. Once more, we are confident that good solutions for this problem will also be generated by a route-based approach since this will avoid the typical drawbacks of vague request assessments. Another problematic assumption is that all carriers have an automated tool for solving a combined request selection and pickup and delivery problem, and that they are willing to apply this tool in several iterations of temporary winner determination and in each such iteration to provide details of hundreds of the best solutions found. Although no direct cost information is revealed, this might be problematic and will probably only be accepted by the carriers if it can be guaranteed that this information will not be interpreted by the agent.

Some further topics still have to be investigated in future. As reported in Sect. 5.1, by combining different classes of PDPTW instances (Sets `LC1`, `LR1`, and `LRC1` or Sets `LC2`, `LR2`, and `LRC2`), the cost-saving potentials of the resulting CTP instances differ strongly from each other. For future research on the strategic level it is a very challenging task to investigate which situations are appropriate for CTP and what preconditions have to be fulfilled for a successful operation of GSs. The second one is to integrate game theoretical considerations like strategic behavior of participants in GSs. It has to be ensured that even when individual participants cheat, e.g., by reporting false evaluation values, the mechanism can still achieve the desired results. In order to provide this, it is important to develop an appropriate profit sharing scheme, especially for the CTP considered in this paper with only limited information available. Another interesting topic is to develop rules for pre-selection of requests for route generation. As observed in Sect. 5.4, if carriers know which requests they do not need to consider, the time used for route generation can be distinctly reduced. To achieve this, certain rules have to be developed and integrated into our mechanism so that the requests can be pre-selected for the route generation. A simple way is to exclude the requests located far away from the depot. Such kind of pre-selection can be either performed by the agent, who prepares a specific request portfolio for each carrier, or by the carriers themselves. This may further improve the performance of the proposed route-based request exchange mechanism in terms of time consumption. In order to successfully utilize this mechanism for much larger CTP instances, heuristic approaches have to be applied to efficiently solve the WDP-SC.

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Appendix: CTP instance generation information

CTP test instances are generated by combining different PDPTW benchmark instances generated by Li and Lim (2001). Table 3 gives the information how these instances are generated. The second column m shows how many PDPTW instances are united. The following columns give the detailed information of each used PDPTW instance in the format “PDPTW_instance (ΔX, ΔY) [number of vehicles]”.

Table 3 Test instance generation information

Instance	m	Generation information				
C101	2	lr103 (0,0) [9]	lc105 (31,7) [10]			
C102	2	lc106 (0,17) [10]	lc108 (23,0) [10]			
C103	3	lc102 (0,15) [10]	lc107 (44,34) [10]	lc109 (13,0) [9]		
C104	3	lc101 (0,0) [10]	lc104 (2,24) [9]	lc105 (28,7) [10]		
C105	4	lc101 (5,56) [10]	lc104 (0,23) [9]	lc107 (47,42) [10]	lc109 (27,0) [9]	
C106	4	lc102 (0,8) [10]	lc103 (35,8) [9]	lc105 (17,33) [10]	lc108 (19,0) [10]	
C107	5	lc101 (3,10) [10]	lc103 (20,29) [9]	lc105 (38,57) [10]	lc107 (0,42) [10]	lc108 (29,0) [10]
C108	5	lc101 (0,9) [10]	lc102 (7,48) [10]	lc103 (43,34) [9]	lc105 (10,0) [10]	lc108 (28,6) [10]
R101	2	lr103 (0,0) [13]	lr110 (20,3) [10]			
R102	2	lr106 (0,0) [12]	lr107 (8,34) [10]			
R103	3	lr102 (0,22) [17]	lr111 (36,29) [10]	lr112 (19,0) [9]		
R104	3	lr107 (3,0) [10]	lr108 (0,47) [9]	lr110 (16,31) [10]		
R105	4	lr106 (0,19) [12]	lr108 (23,19) [9]	lr109 (5,58) [11]	lr112 (12,0) [9]	
R106	4	lr101 (3,10) [19]	lr102 (0,50) [17]	lr105 (36,0) [14]	lr111 (26,30) [10]	
R107	5	lr102 (0,19) [17]	lr105 (14,0) [14]	lr107 (31,22) [10]	lr110 (18,35) [10]	lr112 (3,47) [9]
R108	5	lr101 (0,34) [19]	lr107 (33,50) [10]	lr108 (47,55) [9]	lr111 (7,9) [10]	lr112 (26,0) [9]
RC101	2	lrc103 (0,0) [11]	lrc107 (13,23) [11]			
RC102	2	lrc105 (0,0) [13]	lrc107 (1,47) [11]			
RC103	3	lrc102 (0,19) [12]	lrc103 (12,40) [11]	lrc104 (28,0) [10]		
RC104	3	lrc104 (0,8) [10]	lrc105 (17,31) [13]	lrc106 (31,0) [11]		
RC105	4	lrc101 (0,10) [14]	lrc103 (15,29) [11]	lrc107 (30,45) [11]	lrc108 (22,0) [10]	
RC106	4	lrc102 (0,20) [12]	lrc104 (45,20) [10]	lrc106 (12,57) [11]	lrc107 (39,0) [11]	
RC107	5	lrc101 (5,15) [14]	lrc104 (20,32) [10]	lrc106 (41,0) [11]	lrc107 (0,39) [11]	lrc108 (53,48) [10]
RC108	5	lrc101 (0,17) [14]	lrc102 (3,38) [12]	lrc103 (29,20) [11]	lrc105 (24,54) [13]	lrc107 (12,0) [11]

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