Rolling Horizon Planning Approaches for a Dynamic Collaborative Routing Problem with Full Truckload Pickup and Delivery Requests

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Abstract

In order to improve the operational efficiency of small and mid-sized freight carriers, collaborative transportation planning (CTP) approaches enabling an exchange of customer requests are proposed for horizontal carrier coalitions. Through request exchange carriers can further reduce their costs of fulfilling customer requests compared to the case of isolated planning in which no request is exchanged. In order to exploit the potentials of cost-savings embedded in CTP, appropriate request exchange mechanisms have to be developed. In this paper, the dynamic CTP problem of a coalition of full truckload freight carriers is studied. Two rolling horizon planning approaches are developed to solve the dynamic routing problems. It is further analyzed how the planning results especially the cost reduction realized by performing CTP are influenced by different planning settings. Computational experiments show that the planning results of CTP are obviously superior to those obtained by isolated planning, and the realized cost-savings in percent remain relatively constant, independently of the test settings.

Keywords: dynamic collaborative transportation planning problem, dynamic pickup and delivery problem, rolling horizon planning, horizontal carrier coalition, request exchange, distributed decision making

1. Introduction

A key element of a successful operation of freight carriers is to keep the fulfillment of their customer transportation requests highly efficient. Due to the relatively limited business size, it is much more difficult for small and mid-sized carriers to reach the same level of operational efficiency that large forwarding companies can achieve on average, since the later ones can consolidate requests to a high extend by exploiting the economy of scale. Building horizontal coalition and seeking for cooperation with fellow companies may be considered as a promising remedy.

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In a horizontal carrier coalition, an effective way to reduce member carriers’ costs is to exchange their customer requests with each other and to make the fulfillment plan of all their requests in a collaborative way. Through exchanging requests within the coalition, freight carriers can consolidate complimentary requests of different members and construct more efficient vehicle routes. This can lead to a reduction of their operational costs of up to 30 percent (Cruijssen and Salomon, 2004; Cruijssen et al., 2007a; Krajewska et al., 2008). These cost-saving potentials can be realized by applying a centralized planning while all request information and decision-making competences are transferred to a planning authority of the coalition. In case that coalition members want to preserve their private information and autonomy of decision-making, decentralized planning approaches have to be developed. Wang and Kopfer (2013a) refer to this decentralized planning of freight carriers in horizontal coalitions as collaborative transportation planning (CTP).

According to Stadtler (2009), CTP can be understood here as a joint decision making process for aligning plans of individual members with the aim of achieving coordination in light of information asymmetry. This means that private information and autonomy of coalition members will be preserved locally while the quality of the plans of all members is intended to be improved. In CTP, all member carriers generate plans only for themselves and try to harmonize their plans with those of other members in the coalition by applying appropriate request exchange mechanisms. The specific goal of CTP is to reallocate all member carriers’ requests among them so that the total costs will be smaller than the sum of the carriers’ individual fulfillment costs without any cooperation. The obtained cost-savings present the joint benefits of the coalition that cannot be achieved individually. The profitability of the carriers can then be improved by acquiring their shares of the joint benefits.

CTP has been investigated by many researchers in the last decade. However, the majority of their research focuses on the static CTP problems (SCTPP), in which all information is available a priori at the time CTP is performed. On the contrary, little attention has been paid to dynamic CTP problems (DCTPP). In this paper, the DCTPP with FTL pickup and delivery requests (DCTPPFL) is introduced. Two rolling horizon planning approaches that solve SCTPP periodically based on the updated current information are used to solve the DCTPPFL. The first one is introduced in Wang and Kopfer (2013a) and solves a new SCTPP when a predefined interval is reached. In the other approach, SCTPP is solved whenever a new request becomes urgent and must be irrevocably planned at that time. The purpose of the study in this paper is to analyze how the planning results are influenced by applying different planning strategies. Especially, the contribution of our paper lies in comparing the cost-saving effects of improving individual planning techniques and performing CTP with coalition members as well as in analyzing how the cost-reduction realized by performing CTP in a dynamic environment changes with different planning settings.

This paper is organized as follows. In Section 2, we give a brief literature review on related topics. In Section 3, the DCTPPFL is formally described. In Section 4, the two rolling horizon planning solution approaches are proposed. Computational study and a comprehensive discussion on the results are shown in Section 5. Section 6 concludes this paper.
2. Literature review

The DCTPP extends the SCTPP over a long time horizon with gradually revealed request information. The two closely related topics of this problem are the dynamic and deterministic vehicle routing and the CTP.

2.1. Dynamic and deterministic routing

In contrast to static routing problems where all input data of the problem are known a priori at the time when the routes are constructed, some input data are revealed or updated during the period of time in which operations take place in a dynamic routing problem (Berbeglia et al., 2010). Moreover, a routing problem can be either deterministic or stochastic according to the information quality which reflects possible uncertainty on the available data (Pillac et al., 2013). The reader is referred to Pillac et al. (2013) for a recent review on dynamic routing problems. Specifically, Berbeglia et al. (2010) review the literature on dynamic pickup and delivery problems (PDP). In this section, we focus on some major contributions to dynamic and deterministic routing problems.

Pillac et al. (2013) classify the solution approaches for dynamic routing problems into two categories. The first one comprehends periodic re-optimization approaches. After having constructed a set of initial routes, these approaches periodically solve static problems corresponding to the current states triggered by specific incidences. The first type of such triggers is an update of input data, which practically can be the release of a new customer request. This strategy is used in Psaraftis (1980), Yang et al. (1998), and Yang et al. (2004). Psaraftis (1980) proposes a dynamic programming approach for the dynamic dial-a-ride problem. Rolling horizon approaches are used to solve the real-time FTL PDP with time windows (PDPTW) in Yang et al. (1998) and its extension by the possibility of rejecting requests and soft time windows in Yang et al. (2004).

Alternatively, a re-optimization can be triggered whenever a predefined interval is reached. Savelsbergh and Sol (1998) apply a branch-and-price algorithm to solve the static PDP with time windows for each single re-optimization. Similarly, Chen and Xu (2006) use the column generation scheme in a dynamic approach and solve each time the vehicle routing problem with time windows (VRPTW). An ant colony system is developed in Montemanni et al. (2005) for a dynamic vehicle routing problem in which encrypted information about characteristics of good solutions are conserved in a pheromone matrix and passed on to the next static problem after a predefined duration.

The second category of solution approaches is referred to as continuous re-optimization. The general idea is to run the optimization routines and maintain information on good solutions in an adaptive memory. Whenever an event occurs, e.g., a new request is known or a vehicle has finished its current job, a decision procedure stops the optimization routine and updates the routes. After that, the optimization routine is restarted with the new generated solutions. Different from periodic re-optimization approaches, a driver doesn’t know the next customer to serve until he has finished his current job. Diverse optimization routines are used in these approaches. Gendreau et al. (1999) apply a parallel tabu search (TS) proposed in Taillard et al. (1997). Another TS is proposed in Gendreau et al. (2006) while
the concept of ejection chains (Glover, 1996) is used to construct a powerful neighborhood structure.

In addition to work on developing efficient solution approaches for dynamic routing problems, the influence of different waiting strategies on the quality of solutions to dynamic routing problems is studied in Mitrović-Minić and Laporte (2004). Tjokroamidjojo et al. (2006) analyze how valuable it is for carriers to have the load information in advance.

2.2. Collaborative transportation planning

For small and mid-sized carriers, their relatively limited business size restricts the potential for taking advantage of both economy of scope and economies of scale within vehicle routing. In order to overcome this drawback, freight carriers can seek for partnerships within horizontal collaboration. Some general opportunities and impediments of horizontal cooperation in logistics are revealed in Cruijssen et al. (2007b). A literature review can be found in Cruijssen et al. (2007c).

Through performing CTP with fellow partners in a horizontal coalition, carriers can reduce their operational costs to a great extent. However, appropriate request exchange mechanisms must be developed to exploit the cost-saving potential embedded in CTP. Such mechanisms have to be (1) simple and implementable, (2) effective in terms of generating high joint benefits (Özener et al., 2011), and (3) able to deal with distributed information and decision-making competences (Wang and Kopfer, 2013a).

Some approaches are proposed to tackle this challenging task of solving the SCTPP. Schönberger (2005) propose an approach based on combinatorial auctions (CA) for an SCTPP, in which each member carrier of the coalition has only one vehicle with unlimited capacity. Since time windows constraints are considered, the coalition has not enough capacity to fulfill all the acquired requests and must subcontract some requests to external common carriers. CTP is used to reduce the total costs of the coalition paid to common carriers. Krajewska and Kopfer (2006) propose a generalized model for CTP of carrier coalitions also including three phases: preprocessing, profit optimization, and profit sharing. The authors use a CA to solve a simplified case of SCTPP since they make the assumption that the fulfillment costs for any bundle of requests can be exactly evaluated. An incentive compatible approach using cryptographic techniques for swapping pickup and delivery requests among independent carriers is proposed in Clifton et al. (2008). They develop a protocol that is secure against a centralized model referred to as the “trusted broker” model, where all parties give their input to the broker and the broker computes and returns the result. Schwind et al. (2009) use both a one-round auction and an iterative auction to solve the SCTPP of the profit centers (warehouses) of a single company serving its customers with single commodity goods. The proposed mechanisms try to identify profitable request exchange between adjacent profit centers while each of them independently solves its own VRPTW. Berger and Bierwirth (2010) solve the SCTPP using both a Vickrey auction (Vickrey, 1961) and a CA. Since vehicle capacity is not considered, the underlying routing problem of each coalition member is the traveling salesman problem with pickup and delivery. Özener et al. (2011) study the lane exchange problem of collaborating FTL forwarders and propose bilateral exchange mechanisms. In order to solve the SCTPP of exchanging less-than-truckload
requests with time windows while taking the capacity limit of vehicle fleet into account, a route-based request exchange mechanism is proposed (Wang and Kopfer, 2013a). This approach is further developed in Wang and Kopfer (2013b) to solve the combined problem of CTP and integrated operational transportation planning (Krajewska and Kopfer, 2009). In this new combined problem, all options of request fulfillment including the own fleet, vehicles from dependent subcontractors, vehicles of collaboration partners, and capacities of external common carriers are considered in a holistic way.

In contrast to SCTPP, little research was conducted on DCTPP. Song and Regan (2003) study a variant of DCTPP of a coalition of carriers fulfilling FTL pickup and delivery requests. Whenever a member carrier acquires a customer request, he launches an auction for the assignment of this request and acts as an auctioneer. Other coalition members acting as bidders calculate the marginal costs of inserting this request into their existing routes. The request will be transferred to the bidder with the lowest bid price if this price is lower than the auctioneer’s own marginal costs. Wang and Kopfer (2013a) propose a rolling horizon approach for the DCTPP with predefined time interval between two successive SCTPP. The extended route-based request exchange mechanism in Wang and Kopfer (2013b) is adapted to solve the SCTPP. The results of their computational study show that CTP is especially preferable in a highly dynamic environment. The authors further recommend to use advance information on requests and to plan in a forward-looking way for better solution quality. However, it is not analyzed how the cost-reduction realized by CTP is affected by changes of parameter settings of the CTP approach.

3. Problem definition

The DCTPPFPL deals with a horizontal coalition of independent freight forwarding companies, who offer FTL transportation services for their customers. Each member forwarder in the coalition $i$, $i = 1, \ldots, m$, has an own vehicle fleet $K_i$ with $g_i$ homogeneous vehicles. However, these vehicles are located in different locations at the beginning of the entire time horizon ($t_0 = 0$) and no specific end depots are assigned for them in the dynamic situation. Let $K = \bigcup_{i=1}^{m} K_i$ denote the entire fleet of the coalition. All vehicles in $K$ are homogeneous so that every request in $R$ can be fulfilled by any vehicle in $K$. However, all forwarders may use their own scheme to calculate route costs for their own fleet, i.e., the vehicles may have different variable cost rates $\beta_k$.

Each forwarder $i$, $i = 1, \ldots, m$, in the coalition acquires requests from his customers during the entire time horizon $[0, \infty]$. The set of requests of forwarder $i$ over the entire time horizon is denoted as $R_i$. Let $R = \bigcup_{i=1}^{m} R_i$ denote the set of all requests to be served. A request $r \in R$ must be transported from its pickup location to the corresponding delivery location. At each location $u$, the operation (pickup or delivery) must be started in a customer defined time window $[a_u, b_u]$. The service time at $u$ is given by $s_u$. In a static PDP, all request information is available at the time of planning. In a dynamic PDP, however, requests may be released while the routes are executed. The time when a request $r$ is released to a forwarder is called the release time and denoted as $t^r_{rls}$.  

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In a dynamic environment it is important to define the corresponding set of requests associated with a time point \( t \). At any point of time \( t \), only a subset of requests \( R^t_i \subset R_i \) is known to forwarder \( i \), \( i = 1, \ldots, m \). \( R^t_i \) is defined as the set of all requests acquired by forwarder \( i \) with their release time no later than \( t \), i.e., \( R^t_i = \{ r \in R_i | t_{rls}^r \leq t \} \). Furthermore, the set \( R^t_i \) can be divided into two parts. The first part consists of all requests that have not been planned yet and is denoted as \( R^{t,a}_i \), where the index \( a \) means that these requests are still “active” for the planning. The rest share \( R^t_i \setminus R^{t,a}_i \) is the set of requests that have already been fixed planned and thus are no more relevant for the planning process at the time point \( t \). These requests cannot be reassigned either because their services have already been started or even finished or because their services must be started soon after the time point \( t \).

In order to fulfill a customer request, the forwarder has three options to choose. The first one is the self-fulfillment, i.e., to assign this request to one of the forwarder’s own vehicle. The second one is to subcontract it to common carriers. In case of subcontracting, a certain price \( \gamma_r \) must be paid. The third one is to transfer it to other coalition members through request exchange. The DCTPPFL aims at minimizing the overall costs of the entire coalition to fulfill all requests in \( R \).

In case of isolated planning (IP), in which no request is exchanged among the member carriers, the dynamic transportation planning problem consists of constructing request fulfillment plans for each carrier \( i \) such that all requests in portfolio \( R_i \) are fulfilled either by self-fulfillment or subcontracting. The total costs of IP include the route costs for all vehicles owned by partners and the charge paid to common carriers for subcontracting. In the collaborative planning scenario, carriers have a third request fulfillment option besides self-fulfillment and subcontracting which is to exchange requests with other partners. Requests that are exchanged within the coalition will be exclusively fulfilled using the coalition’s fleet.

4. Solution approaches

In this section, two rolling horizon planning approaches are presented for the DCTPPFL. First, the two basic rolling horizon planning frameworks are presented. Then, some important issues related to the DCTPPFL are described. At last, the extension of the route-based request exchange mechanism that is embedded in the rolling horizon planning frameworks is introduced.

4.1. Rolling horizon planning with fixed interval

The approach used in Wang and Kopfer (2013b) is based on a rolling horizon planning framework with fixed interval, which is denoted as RHP-INT. Figure 1 shows the principle of this framework illustratively.

The entire time horizon is divided into a series of planning periods. All planning periods have the same length \( \tau \). We use index \( p \) to denote the planning periods, \( p = 0, 1, 2, \ldots, \infty \). At the beginning time point \( t_0 = 0 \), an initial plan \( \Pi_1 \) for the first planning horizon including \( H \) following planning periods, i.e., planning periods \( p = 1, 2, \ldots, H \), is constructed. The length of a planning horizon is then given by \( L_H = H \tau \). The plan for the first planning period
is fixed. The plan for the next planning periods $p = 2, \ldots, H$, however, will be actualized in the forthcoming plans as a result of the dynamically released new requests during the execution of planned routes. After that, at the end of each planning period $p - 1$, i.e., at the planning time $t_{p-1} = \left( p - 1 \right) \tau$, $p = 2, 3, \ldots, \infty$, a new plan $\Pi_p$ for the next planning horizon ranging from planning periods $p$ to $p + H - 1$ will be made based on the updated status. Again, the partial plan constructed for planning period $p$ will be fixed while the rest part will be kept changeable. Figure 1 shows the case when $H$ is set to 3.

At each planning time $t_p$, $p = 0, 1, 2, \ldots, \infty$, each vehicle can be assigned some new customer requests after they have finished all the requests that have been planned fixed in its route in the previous planning periods. In case that a vehicle has already finished serving all assigned requests, it waits at the location of the last customer until new orders are assigned.

4.2. Request triggered rolling horizon planning

Another possibility of doing rolling horizon planning is to adjust the plan after each actualization of the status of the request portfolio. This variant is referred to as $RHP-RT$. Figure 2 illustrates the framework of this option.
changed and a new plan is made. The part of the first plan $\Pi_1$ from $t_0$ to $t_1$ has already been executed and thus is the fixed part of $\Pi_1$. The rest part, i.e., from $t_1$ to $t_0 + L_H$ will be actualized due to the new plan. At time point $t_2$, the status of the request portfolio changes again, and the process repeats. As a result, the fixed part of a plan in $RHP-RT$ is dynamically determined through the actualization of the status of the request portfolio.

Different triggers can be used within this framework. In Song and Regan (2003), the trigger is defined as the release of a new request. In their approach, so long as a new request is known to the coalition, the member who acquires it initiates a single-item auction, through which this new request will be fixed assigned. Another option that will be used here is to initiate an exchange process when a request becomes urgent and must be fixed planned immediately. This means that the process is not related with the release time of the requests, but with the *due time* of the requests. The due time $t_r^{due}$ of a request $r$ is defined as the time that is $t_{lead}$ time unit earlier than the latest time when the service of this request must begin, i.e., the end of the time window of the related pickup operation $e_r^+$. Given the predefined lead time $t_{lead}$ for the planning, the due time of a request $r$ can be calculated simply as $t_r^{due} = e_r^+ - t_{lead}$. Figure 3 gives an illustrative explanation of the definition of the due time of requests, where the two rectangles represent the time windows of the pickup and delivery operations of request $r$.

![Figure 3: Due time of a request](image)

### 4.3. Determination of due requests

In a dynamic environment, customer requests are released as time goes on. Some requests may be released just shortly before the latest time when the service must begin and thus need a quick response of the forwarders. Others may be known quite a long time before the time window opens and leave the forwarders much more time to seek for the best plan for their execution. Thus, it is necessary in a rolling horizon planning approach to differentiate requests according to their urgency.

Let $R_i^{t,a}$ denote the set of all active requests of forwarder $i$ at the planning time $t$. An active request at a specific time point is a released yet not executed request that has not been fixed planned previously. The requests in $R_i^{t,a}$ can be further differentiated into two subsets according to their urgency. The most urgent requests are labeled as *due requests* that must be fixed planned at the time $t$, and the remaining part of requests are called *non-due requests* that can be planned at time $t$, but do not need to be fixed planned. Let $R_i^{t,d}$ and $R_i^{t,n}$ denote the sets of due requests and non-due requests, respectively, and we have $R_i^{t,a} = R_i^{t,d} \cup R_i^{t,n}$. Then, the sets of all active, due, and non-due requests of the entire
coalition at the time point $t$ can be defined as $R^{t,a} = \sum_{i=1}^{m} R^{t,a}_i$, $R^{t,d} = \sum_{i=1}^{m} R^{t,d}_i$, and $R^{t,n} = \sum_{i=1}^{m} R^{t,n}_i$, respectively.

Due requests are differently defined in the two different rolling horizon planning frameworks. In case of RHP-RT, a new planning process will be launched when one or more requests becomes due requests. Here, a request $r$ is defined as a due request at any time point $t$ if $t^\text{due}_r \leq t$ holds. More precisely, a request $r$ triggers a new planning when $t^\text{due}_r = t$. The requests that trigger a new planning process are the due requests in this plan.

In the RHP-INT, due requests are not defined based on the due time of requests but in another way. Obviously, at the planning time $t = p\tau$ which is the beginning time of the time period $p+1$, all requests that must be picked up in the next planning period $p+1$, i.e., requests whose service must be started before the end of the planning period $p+1$ at their pickup locations, are due requests. Additionally, in order to improve the continuity of the plan, requests whose pickups must be served soon after the end of the planning period $p+1$ are also considered as due requests in RHP-INT.

4.4. Planning strategies using advance request information

In a dynamic environment, it is undoubted that the earlier the forwarders are given the request information, the better they can do their planning. However, the value of the advance request information is not always the same according to how much advance the information is released (Tjokroamidjojo et al., 2006). For a given request, the shorter the time is from the current time point to the latest time allowed to begin the service, i.e., the more urgent the request is, the more valuable the piece of information about this request is. On the contrary, the longer the time is and the less urgent the request is, the less valuable the related request information is for the planning at the current time. Thus, it is important in a rolling horizon planning to differentiate the known requests according to their urgency to achieve a balance between solution quality and the needed computational efforts.

Based on the differentiation of requests according to their due time, planning strategies using advance request information can be defined based on two factors. The first one is the length of the planning horizon $L_H$. The longer this parameter is, the more forward-looking the planning is. Specifically for RHP-INT, the minimum value of $L_H$ equals to the length of a planning period $\tau$ and the planning focuses only on the most urgent requests. Thus, for the planning with fixed interval, any strategy with $L_h = \tau$ is referred to as myopic planning (MYP), and any strategy with $L_H = H\tau$, $H > 1$, is denoted as forward-looking planning (FLP). For RHP-RT, MYP means that only one request is considered when a static plan is made, i.e., only the costs of moving a vehicle from its current position to the pickup location of this request and bringing the goods then to the corresponding delivery location are considered. In this case, $L_H$ is no more a predefined constant but decided dynamically by the due time of the requests.

The second factor is a weight function that assigns each considered request a weight for the planning that reflects its urgency. This weight can also be interpreted as an evaluation of the advance information of requests. In any MYP this question is easy to answer, since only due requests are considered and all due requests are the same important at the planning time and all of them shall have the same weight value. In the FLP, the situation is more
complicated. Considering the fact that the plan for the non-due requests will be actualized in the following plans in a FLP and thus these requests are not equally important at that moment of planning as the due requests, the importance of these two types of requests must be accordingly differentiated. This can be done by multiplying the outsourcing prices for the requests with different weights. It is worth mentioning that by setting the weight of requests that are to be served after the time point \( t + L_H \) to zero, the term \( R_{t,a}^{d} \) can still be used for the rolling horizon planning framework with a constant \( L_H \). Thus, we also use \( R_{t,a}^{d} \) to denote all known requests in the next planning horizon at any planning time \( t \). In the collaborative planning scenario, these two strategies can be formulated by using the corresponding notations \( R_{t,d}^{d} \) and \( R_{t,a}^{d} \).

4.5. Identification of requests for exchange

A planning strategy using advance request information specifies which requests to consider in each static planning and how these requests should be evaluated based on their due time. However, for the CTP, it has still to be determined which requests are to be exchanged.

This question is easy to answer for \( RHP-RT \). Since a CTP will be launched when some requests become due and must be fixed planned at that moment, all these requests that trigger the plan are to be exchanged.

In case of \( RHP-INT \), two situations have to be differentiated: MYP and FLP. The question can still be easily answered in case of MYP that deals only with those requests in \( R_{t,d}^{d} \). All requests in \( R_{t,d}^{d} \) are considered in the planning and all of them are to be fixed assigned among the coalition members through request exchange. For the FLP, however, all known requests \( R_{t,a}^{d} \) in the next \( H \) planning periods are considered in constructing the plan. Nonetheless, only the most urgent requests, i.e., the requests in \( R_{t,d}^{d} \), for which the plan must be fixed, will be exchanged. Actually, MYP can be realized by setting the weight for all requests in \( R_{t,n}^{d} \) to zero and thus be regarded as a special case of FLP in a broader sense.

It is important to differentiate the requests to be considered and those to be exchanged in case of FLP. The reason is that each reallocation of requests is associated with transfer payments among the members which are determined based on the costs of routes. These costs are supposed to be as accurate as possible. In a dynamic environment, these costs can only be precisely determined for the partial routes serving the most urgent requests since they will not be changed during their execution. Another important reason is that although request information in advance should be considered in planning, the plan for requests that are not urgent should not be fixed as soon as the plan is made (Tjokroamidjojo et al., 2006).

4.6. Extended route-based request exchange mechanism

In order to solve the DCTPPFL, the route-based request exchange mechanism of Wang and Kopfer (2013a) is extended to solve the static problem periodically within the rolling horizon frameworks. Figure 4 gives an overview of the entire process of the route-based request exchange mechanism.
Each time a new planning is initiated at time $t$, all partners first propose all their active requests $R_{i}^{t,a}$ into the common request pool of the coalition in the preprocessing stage. The request set of the coalition $R_{i}^{t,a} = \bigcup_{i=1}^{m} R_{i}^{t,a}$ is then divided into $R_{i}^{t,d}$ and $R_{i}^{t,n}$ that represent the sets of due and non-due requests, respectively. The set $R_{i}^{t,d}$ is also the set of requests to be assigned by the static CTP.

After the requests have been proposed, each forwarder $i$ solves for himself a routing problem using his own fleet only for their own requests $R_{i}^{t,a}$. Through introducing a weight $w_{r}^{t}$ for each request $r \in R_{i}^{t,a}$, the objective function of this routing problem can be formulated as follows.

$$
\min \sum_{k \in K_{i}^{t}} \sum_{(u,v) \in A_{i}^{t}} \beta_{k} d_{uv} x_{uvk} + \sum_{r \in R_{i}^{t,a}} \gamma_{r} w_{r}^{t} z_{r} \quad (1)
$$

The set $K_{i}^{t} \subseteq K_{i}$ is the set of vehicles that are available in the current planning. $A_{i}^{t}$ is the set of arcs defined by forwarder $i$’s own requests and vehicles and $d_{uv}$ is the distance of the arc $(u,v)$. The decision variable $x_{uvk} \in \{0, 1\}$ indicates if an arc $(u,v)$ is used in vehicle $k$’s route and the other binary variable $z_{r}$ indicates if a request is outsourced to a common carrier. In case of MYP, all requests in $R_{i}^{t,n}$ have $w_{r}^{t} = 0$ and all due requests have a weight of one. In case of FLP, all due requests also have the weight of one while other requests have a weight less than one. Next, each forwarder declares the total costs for his own request portfolio $R_{i}^{t,d}$ as a transfer price, which is the maximum payment for the fulfillment of these requests without cooperation. In case of FLP, a route may have both due and non-due requests. Only the first part containing the due requests is considered, i.e., the partial route costs until the delivery location of the last due request in a route are used. Denote this transfer price as $C_{i}^{t,d}$. The total transfer prices $TC_{IP}^{t,d} = \sum_{i=1}^{m} C_{i}^{t,d}$ represent the total costs for due requests at $t$ without cooperation. This information is used for the acceptance of CTP solutions, which will only be accepted when they are better than the solutions of IP, i.e., $TC_{CTP}^{t,d} < TC_{IP}^{t,d}$.
The next step is the *initial route generation*. Each forwarder $i$ solves a routing problem for his own available vehicles $K^t_i$ and generates a set of routes fulfilling the requests selected from the request pool $R^{t,a}$. The objective function is the same as (1) except that the sets $A^t_i$ and $R^{t,a}_i$ are replaced by $A^t_i$ and $R^{t,a}_i$, respectively.

$$\sum_{k \in K^t_i} \sum_{(u,v) \in A^t_i} \beta_k d_{uv} x_{uvw} + \sum_{r \in R^{t,a}_i} \gamma_r w_r z_r$$  \hspace{1cm} (2)

Through solving this problem in a heuristic manner, a set of different solutions can be obtained. The first part of the routes in these solutions containing only the due requests is reported as candidate routes to the agent. The costs of the partial routes will be declared as the costs of these candidate routes.

After the set of candidate routes has been initialized, the iterative process starts. In each iteration, the agent solves the WDP in form of an LP-relaxed SPP to minimize the total fulfillment costs of all due requests. That the requests can be outsourced to common carriers is also considered in the WDP in such a way that each due request $r \in R^{t,d}$ is either to be assigned to a winning candidate route or common carriers for the price $\gamma_r$. This price is the same to all coalition members.

Suppose that there are $n^t$ requests in $r \in R^{t,d}$ and $b_i$ candidate routes have been proposed by forwarder $i$ in the *initial route generation* step. For each request $r$, a fictive route representing the common carrier option with the route cost of $\gamma_r$ is also added into the set of candidate routes. Thus, $b = \sum_{i=1}^m b_i + n^t$ candidate routes are there in total. Let $a_{rj} = 1$ indicate that request $r$ is in route $j$ and $a_{rj} = 0$ otherwise, $j = 1, 2, \ldots, b$. We use $f_{kj} = 1$ to indicate that route $j$ is proposed for vehicle $k$, $k \in K^t$. The cost of a candidate route is denoted by $c_j$. The WDP can be formulated as follows by introducing the binary variable $y_j$, $j = 1, 2, \ldots, b$ to indicate whether a route is chosen as a winning route.

$$\min \ TC^d_{CTP} = \sum_{j=1}^b c_j y_j$$  \hspace{1cm} (3)

subject to:

$$\sum_{j=1}^b a_{rj} y_j = 1 \hspace{0.5cm} \forall r \in R^{t,d}$$  \hspace{1cm} (4)

$$\sum_{j=1}^b f_{kj} y_j \leq 1 \hspace{0.5cm} \forall k \in K^t$$  \hspace{1cm} (5)

Constraints (4) make sure that each request is assigned to exactly one winning route and constraints (5) ensure that each vehicle is assigned to no more than one route. The agent solves the linear relaxation of this model and gets the dual values related to (4) for requests $\pi_r$ and related to (5) for vehicles $\sigma_k$. These values are sent back to the forwarders for the next iteration of route generation.
Using this feedback information, forwarders can generate and submit new candidate routes in the iterative route generation step by solving another routing problem with the following objective function:

$$
\min \sum_{k \in K_t^i} \sum_{(u,v) \in A^p} \beta_k d_{uv} x_{uvk} + \sum_{r \in R^{i,d}} \pi_r z_r + \sum_{r \in R^{i,a}} \gamma_r w_r^i z_r \tag{6}
$$

Again, only the first part of each route in the solutions obtained by using heuristic algorithms is proposed as a candidate route. The ALNS heuristic presented in Wang et al. (2013) is used to generate candidate routes in both the initial and iterative route generation steps.

Iterative route generation ends when predefined criteria are satisfied. The whole process ends with the final winner determination step, in which the agent solves an SCP-based formulation of the WDP by replacing (4) with

$$
\sum_{j=1}^{b} a_{rj} y_j \geq 1 \quad \forall r \in R^{i,d} \tag{7}
$$

If some requests belong to more than one winning route in the WDP solution, the agent calls a simple repair routine to obtain a feasible solution for the CTP problem. The result of the WDP will only be accepted if its total costs are less than the total transfer prices reported by all members in the first phase, which indicates a cost reduction for the entire coalition.

5. Computational experiments

In this section, a comprehensive computation study including several tests is conducted to obtain some insights into DCTP. Specifically, the tests are designed to answer the following three questions. Firstly, how much cost-saving potential can be realized by using the approaches proposed in Section 4. Secondly, how the overall planning results are influenced by different factors such as planning strategies and characteristics of the instances. Last but not least, how the realized cost-savings through CTP against IP are affected by these factors.

5.1. Test case generation

For our computational experiments new theoretical instances are generated. In the first step, ten static instances are generated in total. The procedure of generating static instances begins with generating request information in an iterative fashion. The length per planning period is set as $\tau = 100$. In each iteration $it$, $it = 1, \ldots, 45$, which corresponds to the time interval with $[\tau \cdot it, \tau \cdot it + \tau]$, about 40 requests for the entire coalition are generated. In order to capture fluctuation of customer demands, this number is adjusted randomly with an amount up to $\pm 20\%$. These requests are then assigned to three coalition forwarders according to the request weights, which are also randomly generated in $[0.7, 1.3]$ for each forwarder in each iteration.
Pickup and delivery locations of requests are randomly distributed in a square of size 200 × 150. The distance between any two location nodes is the Euclidean distance. For more than 80% of all requests, the distance between pickup and delivery locations lies in the range from 20 to 160 and the average value is about 90. The time windows for a request \( r \) generated in iteration \( it \) are defined in the following way. Let \( r^+ \) and \( r^- \) represent the pickup and delivery locations of request \( r \). In the first iteration \( (it = 1) \), \( b_{r^+} \) is given a random value in \([\tau/3, \tau]\). In the following iterations, \( b_{r^+} \) is given a random value in range \((\tau \cdot it, \tau \cdot it + \tau)\). \( e_{r^+} \) is calculated by adding \( b_{r^+} \) with a time window width, which is determined as \( \tau/2 \pm 30\% \). The time window for the delivery location \([b_{r^-}, e_{r^-}]\) is simply defined as \([b_{r^+} + d'_{r+r^-} + s_{r^+}, e_{r^+} + d'_{r+r^-} + s_{r^+}]\), while \( d'_{r+r^-} \) is the driving time from \( r^+ \) to \( r^- \) and \( s_{r^+} \) is the service time at \( r^+ \). All operations are assigned the same service time of 10. Since the execution of some requests generated in the last iteration \( it = 45 \) may be finished later, the entire time horizon of the instances is \([0, 4800]\).

Each forwarder is assigned a vehicle fleet. The number of vehicles is determined as the average request number per planning period with a deviation of up to ±30%. Vehicles are located at randomly generated start locations with empty load at the very beginning \( t_0 \). The average number of vehicles per forwarder in an instance is 13.3, while the concrete numbers are varying from 9 to 17. Fixed costs of vehicles \( \alpha_k \) are supposed to be the same by all forwarders so that they can be ignored in the computational study. The velocity of all vehicles is assumed to be one so that the driving time between two nodes equals the distance. The variable cost rate \( \beta_k \) for a DU is set to one for all vehicles \( k \in K \).

Since requests are allowed to be transferred to common carriers, the price for outsourcing requests must also be specified. This cost \( \gamma_r \) for a request \( r \) is calculated as \( \gamma_r = \varphi d_r \theta^{d_r} \), where \( \varphi \) is a constant cost rate per DU and \( d_r \) is the adjusted travel distance between pickup and delivery locations. The basic cost rate \( \varphi \) is given the value of 2 that is twice as high as the variable cost rate of the vehicles \( \beta_s \) and the adjusted travel distance is defined as \( d_r = \max\{5, d_{r^+} - \ldots\} \). The motivation to use the adjusted travel distance is that the common carriers charge a fixed minimum fee for each request if the distance to travel lies below a specific level. \( \theta \) is a parameter which is set to 0.9986. \( \theta^{d_r} \) can be seen as a distance-dependent discount on the cost rate. The introduction of \( \theta \) captures the fact in practice that freight rates reduce with increasing transportation distance.

The second step is to assign each request \( r \) a release time \( t^{'t^d}_{r^d} \) to make a static instance to a dynamic one. Denote the span between the release time \( t^{'t^d}_{r^d} \) of a request \( r \) and the beginning of the time window of the corresponding pickup operation \( b_{r^+} \) as \( t^{l^d}_{r} = b_{r^+} - t^{'t^d}_{r^d} \), the new instances are generated in such a way that 5% requests have \( t^{l^d}_{r} = 450 \), 10% \( t^{l^d}_{r} = 400 \), 10% \( t^{l^d}_{r} = 350 \), 15% \( t^{l^d}_{r} = 300 \), 30% \( t^{l^d}_{r} = 250 \), 20% \( t^{l^d}_{r} = 200 \), and 10% \( t^{l^d}_{r} = 150 \).

### 5.2. Test 1: Value of request information in advance

An important lesson that can be learned from the computation study of Wang and Kopfer (2013b) is that even when forwarders are offered the information about the requests that are to be fulfilled in the far future, they do not need to consider them in the planning immediately. In the framework \( RHP-INT \), this differentiation of requests according to their
urgency can be done by choosing a proper weight function (see Section 4.4). Test 2 is thus designed to answer the question, what this function should be.

In this test, RHP-INT is used for solving the DCTPPFL and three different planning strategies are tested. The first reference strategy is the MYP, which totally ignores the requests that are not urgent. The second reference strategy is to consider all known requests. This specification of the FLP is denoted as FLP-I. The last strategy is an FLP that only considers future requests to limited extend and is denoted as FLP-II.

5.2.1. Simulation settings

The strategy of MYP can be simply realized by assigning due requests the weight of one and non-due requests the weight of zero. For FLP-I, the weight of due requests is one. Non-due requests with \((p + 1.25)\tau < e_{r+} \leq (p + 2)\tau\) have a weight of 0.75 and all other non-due requests have a weight of 0.56. The weight distribution in the FLP-II is specified as follows. Due requests that must be served in \((p + 1.25)\tau\) have a weight of 1. Non-due requests with \((p + 1.25)\tau < e_{r+} \leq (p + 2)\tau\) have a weight of 0.75. Non-due requests with \((p + 2)\tau < e_{r+} \leq (p + 2.5)\tau\) have a weight of 0.56. The remaining known requests are ignored and assigned a weight of zero. As the length of each planning period \(\tau\) equals 100, the lengths of the planning horizon of each static planning of the three strategies MYP, FLP-I, and FLP-II are then 125, \(\infty\), and 250, respectively.

5.2.2. Results and discussion

In order to identify the cost-savings that can be realized by using RHP-INT, the scenarios IP and CTP are simulated. Each instance has been solved three times. The average values of the results obtained in the three trials of all ten instances are summed up and given in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>MYP</th>
<th>FLP-I</th>
<th>FLP-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP</td>
<td>236199.37</td>
<td>235382.59</td>
<td>235401.93</td>
</tr>
<tr>
<td>CTP</td>
<td>220956.44</td>
<td>220703.65</td>
<td>220571.02</td>
</tr>
<tr>
<td>(\Delta C_{CTP})</td>
<td>15210.56</td>
<td>14714.79</td>
<td>14830.91</td>
</tr>
<tr>
<td>(\Delta C_{CTP}(%))</td>
<td>6.44</td>
<td>6.25</td>
<td>6.30</td>
</tr>
</tbody>
</table>

The total costs of the plan over the entire time horizon of the coalition with and without cooperation are given in the second and third rows. It is clear that CTP outperforms IP with all planning strategies from MYP to FLP-II. The realized cost-savings are given in the fourth row in absolute value and in the fifth row in percentage. In all cases, CTP can realize over 6% cost-savings compared with the results without horizontal cooperation. The best average result of IP is achieved by using the planning strategy FLP-I and of CTP by using FLP-II. From a further comparison of the total costs between FLP-I and FLP-II it can be concluded that FLP-II performs equally well as the more time-consuming strategy FLP-I. This result confirms the hypothesis made based on the results of Test 1 that requests to be fulfilled in far future do not need to be considered in the current planning process to get good quality solutions.
Table 2: Cost-savings through forward-looking planning

<table>
<thead>
<tr>
<th></th>
<th>FLP-I</th>
<th></th>
<th>FLP-II</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>∆(C_{FLP})</td>
<td>∆(C_{FLP})%</td>
<td>∆(C_{FLP})</td>
<td>∆(C_{FLP})%</td>
</tr>
<tr>
<td>IP</td>
<td>816.78</td>
<td>0.35</td>
<td>797.44</td>
<td>0.34</td>
</tr>
<tr>
<td>CTP</td>
<td>252.79</td>
<td>0.11</td>
<td>385.42</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 2 shows the cost-savings of FLP compared to MYP. The cost-savings in columns two and four are calculated by subcontracting the total costs resulted in FLP-I and FLP-II from the total costs of the results of MYP. The relative values of the cost-savings are then given in columns three and five. It is clear that in both IP and CTP, FLP can lead to better solutions. Especially, FLP can realize more percentage of cost-savings in IP than in CTP. However, if we compare the cost-savings realized by planning in a forward-looking way with those realized by using CTP, it can be concluded that collaboration is much better. Even the worst solution of CTP that is obtained by MYP is much better than the best solution of IP (FLP-I) and the coalition can realize as many as over 18 times cost-savings (6.44% vs. 0.35%) than the best case of IP.

Through the discussion about the results of Test 1, some important conclusions and suggestions can be drawn for freight forwarders. Firstly, information about requests in the future is valuable and has to be considered in each static planning process in a rolling horizon planning framework. However, requests that are to be fulfilled in far future can be ignored without necessarily worsening the overall results. For a single forwarder, it is recommendable to use request information offered in advance to reduce the total costs. However, CTP is obviously more efficient in reducing costs. Compared with cooperation, the benefits of improving individual planning strategy become negligible and this finding coincides with that of Wang and Kopfer (2013b). Forwarders should seek for cooperation with proper partners for cost reduction. Cost benefits to a considerable extend can be realized by CTP even with simple strategies as MYP in this test. Nonetheless, the overall best results are achieved by combining CTP with FLP.

Another interesting observation is that the cost-savings through CTP using all three planning strategies are on the same level. It seems that for a given configuration of RHP-INT, the reduced costs through CTP against IP remain stable. The next two tests are then designed to examine this hypothesis by varying the length of the planning horizon \(L_H\) (in case of RHP-RT) and the length of the planning period \(\tau\) (in case of RHP-INT) of the rolling horizon planning and to find out good values of these important parameters. Since FLP-II performs equally well as FLP-I but requires significantly less computational efforts, the forward-looking planning strategy FLP-II is used in the next tests.

5.3. Test 2: Length of the planning period in RHP-INT

Test 2 is designed to identify the best length of the planning period in RHP-INT, given a such weight function that is described in the last section for FLP-II. The length of the planning period is \(2.5\tau\) according to this function, as requests with \(e_r + \tau\) later than \(t + 2.5\tau\) will be excluded from the planning at time \(t\).
5.3.1. Simulation settings

In this test, six different $\tau$-values: 25, 50, 75, 100, 125, and 150 are tested. Since the entire time horizon is fixed, the number of total planning periods can be calculated simply by $4500/\tau + 1$. Note that the last 300 TU in the entire time horizon are reserved to make sure that the service of all requests can be finished and the last planning period is defined as $[4500,4800]$ for all $\tau$-values. For instance, by setting $\tau = 25$, the entire time horizon is divided into 181 planning periods and the first plan is made at time $t = 0$ and the last one is made at $t = 4,500$. For the largest $\tau$-value of 150, there are only 31 planning periods.

In order to determine the cost-savings that can be realized by using the proposed approach, the two scenarios IP and CTP are simulated in this test. Each instance has been tested three times in each of these two scenarios and the average values of these three trials are calculated for each instance.

5.3.2. Results and discussion

The results of the simulation are given in an aggregated form in Table 3. The costs given in the second and third rows are the average values of the ten instances. The last two rows give the realized cost-savings (absolute and relative) through CTP.

<table>
<thead>
<tr>
<th>$\tau$</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP</td>
<td>240997.53</td>
<td>236092.67</td>
<td>236446.13</td>
<td>235401.93</td>
<td>235886.31</td>
<td>236949.87</td>
</tr>
<tr>
<td>CTP</td>
<td>226821.20</td>
<td>220726.27</td>
<td>221809.72</td>
<td>220571.02</td>
<td>221722.27</td>
<td>223548.80</td>
</tr>
<tr>
<td>$\Delta C$</td>
<td>14176.33</td>
<td>15366.40</td>
<td>14636.41</td>
<td>14830.91</td>
<td>14164.04</td>
<td>13401.07</td>
</tr>
<tr>
<td>$\Delta C(%)$</td>
<td>5.88</td>
<td>6.51</td>
<td>6.19</td>
<td>6.30</td>
<td>6.00</td>
<td>5.66</td>
</tr>
</tbody>
</table>

To ease an analysis of the results, the costs in Table 3 are illustrated in Figure 5. Two interesting characters can be observed from this figure. The first one is that the curves depicted in this figure have a “W”-shape, and the other one is that the two curves are nearly parallel to each other.

It is not surprising that a too small or a too large $\tau$-value leads to inferior solutions. If the $\tau$ is given a very small value (25), the results tend to be worse than a moderate value, e.g.,
100. The reason lies in the high frequency of the planning and the short planning horizon with $L_H = 2.5 \times 25 = 62.5$, which is even shorter than the time corresponding to the average transportation length of the requests that is about 93. In this extreme situation, vehicles are only assigned one due request each time and no successive request will be considered, since the time when the service at the assigned due request’s delivery location lies beyond the planning horizon and the possible successive requests will be ignored in the planning.

On the other hand, if $\tau$ is given a large value, the planning process becomes unresponsive to the dynamic of the instances. When $\tau = 150$, the length of the planning horizon is 375, which is much longer than the average time used to transport the goods from a request’s pickup location to the corresponding delivery location. In this case, the planning process tries to fix the plan for too many requests so that the resulted plans are too rigid to be competitive with those obtained by configuring the RHP-INT with moderate $\tau$-values.

In order to better understand the two valleys of the “W”-shape of the curves, it is helpful to take a glance at the composition of the total costs firstly, which is shown in Figure 6.

![Figure 6: Cost composition of the results of Test 2](image)

Since subcontracting is introduced in the DCTPPFL, the quality of the results depends not only on good routing, but also on a good decision on the fulfillment modes for each single request. The basic principle used in the mode selection is to compare the insertion cost $\Delta C_r$ of a request $r$ and the outsourcing price $\gamma_r$. In this problem, $\Delta C_r$ depends on both the distance between its pickup and delivery locations and the distances to the previous and successive nodes in the route that will be connected with $r^+$ and $r^-$. Generally speaking, the shorter the planning period is, the less requests are considered in the planning. In this case, there exist few opportunities to bundle requests and to generate efficiency routes. As a result, the repositioning costs caused by sending vehicles from one request to another also tend to be higher than in planning with longer planning period. The average insertion cost also increases with decreasing number of requests to be planned each time. On the contrary, if more requests are to be inserted into a route due to a longer planning period, the possibility that they can be well bundled so that better routes can be found increases. The distance from a delivery node to the pickup location of the next request also tends to be shorter. In other words, the shorter the planning period is, the
more expensive it is in average to insert requests into routes and the higher the possibility is to outsource requests to common carriers. This can be intuitively understood as such that the planning prefers subcontracting against self-fulfillment in the mode selection with small $\tau$-values. This is the reason why the outsourcing costs of the plan with $\tau = 25$ are remarkable higher than other cases that can be seen in Figure 6.

With increasing length of the planning period, there are more and more requests that can be well bundled in each planning and the routes become longer and longer. The preference of the planning process on outsourcing exists with increasing $\tau$-value until some time when the insertion costs are reduced to a level that is slightly lower than the outsourcing costs. The reduction of the insertion costs in general leads to the change of the preference on fulfillment mode from subcontracting to the coalition’s vehicles. This point is reached in this test at $\tau = 50$. The new strong preference of mode on vehicles makes the approach try to put requests into vehicle routes as many as possible. The result is the highest level of route costs and the lowest level of the outsourcing costs. In total, the overall results are the second best solution in both IP and CTP scenarios.

When $\tau$ further increases, the relationship between the meaning of the due requests and non-due requests in the planning changes. A small $\tau$-value indicates a short planning horizon. The majority of the time in each planning period is used merely for the fulfillment of the due requests. The candidate routes generated in the planning consist of almost only the due requests. This means that due requests are emphasized much more than non-due requests. In a planning with large $\tau$-values, i.e., long planning horizons, longer routes are generated, in which after the due requests also non-due requests are planned. The non-due requests to be planned in the next planning periods are thus emphasized more than in planning processes with small $\tau$-values. In other words, small $\tau$-values emphasize the near future and large $\tau$-values emphasize a more smooth plan over a longer time. A clear preference with a proper configuration, either better plans for the near future ($\tau = 50$) or smooth plans ($\tau = 100$) can help find good solutions in general, while the configuration with $\tau = 75$ with an unclear preference leads to worse results. But is must be mentioned here that that $\tau = 75$ means an unclear preference only refers to the average performance. As a matter of fact, this configuration leads to clear emphasis and in turn the best results of three instances.

The benefits of CTP can be clearly seen from Figure 5. In all cases, CTP obviously outperforms IP and has realized considerable cost-savings, which account to 5.88%-6.51%. Moreover, the two curves of the total costs are almost parallel. It indicates that the performance of the CTP is very stable against the choice of the $\tau$-value and CTP is always about 6% better than IP. For a single freight forwarder this means that (1) he can improve his planning by choosing the proper configuration of the rolling horizon approach, and (2) he can always achieve a further noticeable improvement that remains relatively constant no matter what configuration has been chosen by request exchange within collaboration.

On the other hand, the cost-savings with large $\tau$-values are generally less than those with small values. It can be explained by the fact that in planning with short planning horizons, the members can hardly construct efficient routes in IP. In the CTP scenario, however, the coalition has a larger request pool as well as a larger fleet so that switches of requests among
the members can considerably improve the results. On the contrary, a long planning horizon means at the same time a large number of requests to be planned in each planning period and the members can also better bundle their requests in IP. As a result, the potential of CTP for further improvement of the routes decreases a little. This observation also indicates an important conclusion that in dynamic environment, CTP tends to be even more useful to reduce costs than in static planning.

5.4. Test 3: Length of the planning horizon in RHP-RT

Test 3 is designed in the same way as Test 2 to analyze the influence of different lengths of the planning horizon configured in the planning framework RHP-RT on the performance of the rolling horizon approach.

5.4.1. Simulation settings

In the planning framework RHP-RT there is no planning period defined. However, in order to make it possible to compare the performance of RHP-INT and RHP-RT, a fictive planning period can be introduced in this test, which takes the same values as tested in Test 2. Using the same weight function the two approaches will have the same length of the planning horizon $L_H$ when the same $\tau$-value is given.

Different as in RHP-INT, the number of plannings of the RHP-RT approach does not depend on $L_H$ but the number of requests in total. The average number of requests of the ten instances is 1,775. As some requests have the same due time and all requests whose due time after $t = 4,500$ are planned at once in the last planning, the number of actually performed plannings in the entire time horizon is somehow less than the number of requests and accounts to in average 1,462. This number also implies that the computational efforts needed for the whole planning increase considerably.

Again, the two scenarios IP and CTP are simulated for each instance. Three trials of simulation ran for each instance and the average value is calculated.

5.4.2. Results and discussion

The results of the simulation are given in Table 4 in the same format as in Table 3 and illustratively plotted in Figure 7.

<table>
<thead>
<tr>
<th>$L_H(\tau)$</th>
<th>62(25)</th>
<th>125(50)</th>
<th>187(75)</th>
<th>250(100)</th>
<th>312(125)</th>
<th>375(150)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP</td>
<td>243523.00</td>
<td>238745.87</td>
<td>238987.03</td>
<td>238105.87</td>
<td>238396.85</td>
<td>239788.12</td>
</tr>
<tr>
<td>CTP</td>
<td>228592.63</td>
<td>223371.96</td>
<td>224721.87</td>
<td>223334.53</td>
<td>224263.84</td>
<td>225244.73</td>
</tr>
<tr>
<td>$\Delta C$</td>
<td>14930.37</td>
<td>15373.91</td>
<td>14265.16</td>
<td>14771.34</td>
<td>14133.01</td>
<td>14543.39</td>
</tr>
<tr>
<td>$\Delta C(%)$</td>
<td>6.13</td>
<td>6.44</td>
<td>5.97</td>
<td>6.20</td>
<td>5.93</td>
<td>6.07</td>
</tr>
</tbody>
</table>

The results of Test 3 reconfirm that CTP is superior to IP. The realized cost-savings account to more than 6% in average. Again, even the worst CTP is much better than the best IP solution. The curves of costs of IP and CTP in Figure 7 have the similar “W”-shape with those in Figure 5. The overall best result is achieved by setting $L_H$ to 250, which is the
same as in Test 3 with $\tau = 100$. The choice of the length of the planning horizon in Tests 3 and 4 seems to be independent on the planning framework.

A straightforward comparison of the performance of the two rolling horizon planning approaches is given by Figure 8. \textit{RHP-INT} is clearly the superior to \textit{RHP-RT} in both IP and CTP scenarios. The extremely high frequency of the change of existing plans over the entire time horizon makes the planning framework of the latter one over sensitive to the dynamic of the instances.

Another interesting observation is that, although using different frameworks can result in different levels of solution quality, all four curves drawn in Figure 8 share the same shape. Moreover, for the tested configurations, they are almost parallel. This means that the choice of planning approach in a dynamic environment has a strong influence on solution quality. On the contrary, the relative performance of different configurations of a specific rolling horizon planning approach remains stable. A practical interpretation is that the individual experience on solving dynamic routing problems can be well used in CTP, either.

5.5. \textit{Test 4: Planning with high subcontracting costs}

The last test in this computational study on the DCTPPFL is to see what happens when the price level of subcontracting dramatically increases. The planning approach based on
RHP-INT is chosen for this test due to its superior performance against RHP-RT.

5.5.1. Instance adjustment and simulation settings

The same instances tested previously in Tests 1-3 are used in this test. However, the subcontracting costs of the requests are increased by 50%. The rolling horizon planning is configured the same as that used in Test 2.

Due to the cost function used for generating the subcontracting price for requests in the instance generation, subcontracting becomes so expensive that for a given request \( r \) with the travel distance \( d_{r+r-} \), the costs of outsourcing can cover almost the vehicle costs for traveling three times as long as \( d_{r+r-} \). Such extremely high costs of subcontracting force the planning to avoid any outsourcing whenever the capacity of the fleet is not exhausted.

5.5.2. Results and discussion

Results of the simulation are given in Table 5 in the same format as in other tests and are illustratively shown in Figure 9.

<table>
<thead>
<tr>
<th>( \tau )</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP</td>
<td>27,956,580</td>
<td>26,947,855</td>
<td>28,931,915</td>
<td>28,931,922</td>
<td>29,031,972</td>
<td>29,385,736</td>
</tr>
<tr>
<td>CTP</td>
<td>25,827,935</td>
<td>24,796,240</td>
<td>26,689,200</td>
<td>26,538,823</td>
<td>26,945,494</td>
<td>27,469,000</td>
</tr>
<tr>
<td>( \Delta C )</td>
<td>212,864.5</td>
<td>215,161.5</td>
<td>224,271.5</td>
<td>221,099.8</td>
<td>208,654.8</td>
<td>191,583.5</td>
</tr>
<tr>
<td>( \Delta C(%) )</td>
<td>7.61</td>
<td>7.98</td>
<td>7.75</td>
<td>7.69</td>
<td>7.19</td>
<td>6.52</td>
</tr>
</tbody>
</table>

The absolute realized cost-savings through CTP increase significantly compared with Test 2, because the whole coalition does not have enough capacity to fulfill all requests and the costs for outsourcing increase dramatically. However, the relative cost-savings given in the fifth row in Table 5 indicate that the more expensive the subcontracting is, the more significant the synergy effect of collaboration is.

![Figure 9: Performance of RHP-INT with high subcontracting costs](image)

Since subcontracting is considered in the DCTPPFL, a feasible solution of the problem is to transfer all requests to common carriers. Due to the extremely high costs of subcontracting, the objective of the problem in this test is almost equivalent to that of reducing
the costs for subcontracting to the greatest extent by selecting and inserting requests into routes. The benefits of inserting an FLT request \( r \) into a vehicle route in the DCTPPFL can be calculated by substituting the increment of the route costs from the outsourcing price. The latter one can be calculated by multiplying the variable cost rate of the vehicle \( \beta \) with the sum of the repositioning distance of the vehicle from its current location to the pickup location of the request \( d_{r+repo}^r \) and the distance for transporting the goods to the delivery location \( d_{r+\cdot}^r \). Then, an index \( \eta_r \) can be introduced to measure the efficiency in reducing costs of the insertion of a request \( r \) into some vehicle route. \( \eta_r \) is defined in (8) as the ratio between the cost reduction of inserting \( r \) into some vehicle route and the non-effective driven distances, i.e., how many costs can be reduced by each DU of repositioning of the vehicle for this requests.

\[
\eta_r = \frac{\varphi d_r \theta^d_r - \beta (d_{r+\cdot}^r + d_{r+repo}^r)}{d_{r+repo}^r}
\]

When \( d_{r+\cdot}^r \geq 5 \), which is the absolute majority in \( R \), \( d_r \) and \( d_{r+\cdot}^r \) are the same because \( d_r = \max\{5, d_{r+\cdot}^r\} \). We can then replace \( d_{r+\cdot}^r \) with \( d_r \) in (8).

Now, we can not take a deeper look at the relationship between \( d_r \) and \( \eta_r \). The partial derivative of \( \eta_r \) with respect to \( d_r \), \( d_r \geq 5 \) is

\[
\frac{\partial \eta_r}{\partial d_r} = \frac{1}{d_{r+repo}^r} \left[ \varphi \theta^d_r (1 + d_r \ln \theta) - \beta \right]
\]

The second order partial derivative of \( \eta \) with respect to \( d_r \) is

\[
\frac{\partial^2 \eta_r}{\partial d_r^2} = \frac{\varphi \ln \theta}{d_{r+repo}^r} (2 \theta^d_r + d_r \theta^d_r \ln \theta)
\]

Since \( \theta = 0.9986 \), we have \( \ln 0.9986 = -0.0014 \). As the maximal length of a single request is the diagonal of the rectangle in which all customer nodes are located, \( d_r \leq 250 \). \( 2 \theta^d_r + d_r \theta^d_r \ln \theta \) is always positive when \( d_r \) takes values in the range of \([5, 250]\). Thus, the second order partial derivative of \( \eta_r \) with respect to \( d_r \) (10) is always negative, which means that the first order derivative (9) is a monotone decreasing function of \( d_r \). The first order derivative of \( \eta_r \) at \( d_r = 250 \) can be calculated using the given values: \( \varphi = 3 \), \( \theta = 0.9986 \), \( \beta = 1 \), and \( d_{r+repo}^r > 0 \).

\[
\left. \frac{\partial \eta_r}{\partial d_r} \right|_{d_r=250} = \frac{1}{d_{r+repo}^r} \left[ 3 \cdot 0.9986^{250} (1 + 250 \cdot \ln 0.9986) - 1 \right] = \frac{0.3733}{d_{r+repo}^r} > 0
\]

The positive value of the first order derivative of \( \eta_r \) indicates that \( \eta_r \) defined in (8) is a monotone increasing function of \( d_r \) for a given \( d_{r+repo}^r \). For each DU driven for the reposition a vehicle to a request, the longer the request is, the more efficient this insertion is. In other words, The more the long requests are subcontracted, the worse the quality of the planning tends to be.

This idea can then be used for a better understanding of the results of this test. A good solution should have two characters. The first one is a good mode decision and the second one is a high efficiency of the vehicle routes. Based on the analysis above, the first character
can be quantified approximately using the average request length of outsourced requests $d^C_r$ of the solution. In general, the smaller this value is, the more requests are planned in vehicle routes and thus the quality of the solution tends to be high. The second character can be quantified by the efficiency of the vehicle fleet $\eta_K$, which is defined as the ratio of total driven distances for repositioning vehicles to the total route lengths of all vehicles in $K$, where $K$ is the entire vehicle set of the coalition. Table 6 gives these two indexes of CTP solutions.

<table>
<thead>
<tr>
<th>(\tau)</th>
<th>(\eta_K)</th>
<th>(d^C_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.134</td>
<td>60.3</td>
</tr>
<tr>
<td>50</td>
<td>0.135</td>
<td>55.2</td>
</tr>
<tr>
<td>75</td>
<td>0.173</td>
<td>62.9</td>
</tr>
<tr>
<td>100</td>
<td>0.175</td>
<td>62.3</td>
</tr>
<tr>
<td>125</td>
<td>0.171</td>
<td>62.4</td>
</tr>
<tr>
<td>150</td>
<td>0.173</td>
<td>63.7</td>
</tr>
</tbody>
</table>

When \(\tau=25\), the whole planning is quite greedy compared with other configurations. Requests with both long and short distances \(d_r\) will be inserted into any vehicle routes each time so long as the capacity restriction is satisfied without considering what happens afterward. Compared with the best result at \(\tau = 50\), this myopic behavior results in a high $d^C_r$-value, which indicates that more requests with longer transport distances \(d_r\) are outsourced, even when the routes are the same efficient.

When \(\tau=50\), more attention is paid to the routing aspect in the dynamic problem than the previous case. On one hand, the planning process still tries to put every request into vehicle route. On the other hand, it also tries to pick up the requests with longer transport distances, even when they are slightly less urgent than some shorter requests. This can be interpreted from the character indexes. The efficiency of vehicle routes is only one pro mile worsen than that when \(\tau=25\), but the mode choice is made in a significantly better way so that the total performance becomes much better.

The unclear preference on greedy plans or smooth plans at \(\tau=75\) also leads in this test to obvious worsening of the solution quality compared with those obtained with \(\tau=50\). Although the results can be improved by increasing \(\tau\) from 75 to 100 somehow, due to the increasing length of the planning period the whole planning process is no more flexible enough to deal with the dynamic of the instances. The intent to reduce great changes in the partial plans for the non-due requests in the following planning periods weakens the capability of the approach to make enough quick responses to new released requests, especially when the distance between the pickup and delivery locations of these requests is long.

Finally, it is necessary to emphasize that the analysis of the results based on the two indexes $\eta_K$ and $d^C_r$ cannot be simply generalized for other tests. In this test, the outsourcing price is extremely high so that it is almost always profitable to fulfill a request with the vehicle fleet rather than outsourcing, even without considering the synergy effect of bundling requests. Precisely, the break even point for a single request can be calculated with a given $d^{\text{repo}}_r$. We can take the CTP results of this test as an example and use the average repositioning distances per request for the calculation. The average value of $d^{\text{repo}}_r$ over all configurations is 21.70 and the break even point lies at $d_r = 11.11$. So long as the transportation distance between the pickup and delivery locations of a request is longer...
than 11 DU, the fulfillment using coalition’s own vehicle is better. For comparison, the break even point for the outsourcing price level in the previous tests calculated using the same average repositioning distance would be at $d_r = 23.19$, which is even longer than the repositioning distance. In this case, the strategy to insert any request into routes in the planning with very small $\tau$-values in this test will not be valid. It is why the average number of outsourced requests of all ten instances in Tests 2 (675) and 3 (696) in the configuration with $\tau = 25$ is significantly smaller than in this test (714).

6. Conclusions

In order to improve the operational efficiency, small and mid-sized freight forwarders are suggested to integrate external transportation resources into their operational planning process. Besides the option to outsource requests to common carriers, they can further reduce costs through setting up horizontal coalition with fellow companies and perform CTP. The static CTP has been studied for different situations in the last decade. However, little research has been conducted to study CTP in a dynamic environment.

Compared with the static CTP, the consideration of the dynamic CTP is a more challenging task in the academic research on transportation logistics. In order to fill the gap in the research on dynamic CTP, the DCTPPFL is introduced and formally defined in this chapter. Although the static problem of the DCTPPFL is the FTL PDPTW, which is relatively simple compared with the PDPTW for LTL requests, the study of the DCTPPFL can help better understand the CTP of forwarder coalitions in dynamic environments and to appeal to more intensive studies in this research area.

In order to solve the DCTPPFL, two rolling horizon approaches are proposed in this chapter, too. The first one is proposed firstly in Wang and Kopfer (2013b). The second one is proposed in this chapter for the first time. The difference between these two approaches lies in the trigger of new planning processes. In RHP-INT, a new planning is triggered by the fixed interval between two consecutive planning processes. In RHP-RT, a new planning process is triggered by the actualization of the status of requests. Both strategies have been used in literature to solve the dynamic routing problems.

A comprehensive computational study on the DCTPPFL is conducted to evaluate the proposed approaches and to derive some practical suggestions for forwarders. In Test 1, different planning strategies using the request information released by customers in advance are tested. The results offer strong supports for the suggestion derived from the results of the computational study conducted by Wang and Kopfer (2013b). It comes out that if forwarders can get the request information in advance, they can improve their planning and reduce costs. However, they don’t need to consider all request information in a forward-looking way, but can ignore the requests that are to be fulfilled in the far future. Notice that the phrase “far future” here has to be understood according to the configuration of the rolling horizon planning and refers to requests that are to be fulfilled not until some planning periods later.

The two rolling horizon planning approaches proposed in Section 4 are tested with different configurations with respect to the length of the planning horizon in Tests 2 and 3.
Results show that the RHP-INT outperforms RHP-RT in terms of both solution quality and computational efforts. The two approaches perform differently in terms of solution quality with different configurations. The choice of the right configuration significantly affects the results. Freight forwarders can thus improve their planning technique to achieve better business performance. However, the more promising way to reduce their operational costs is to seek for cooperation and do CTP by exchanging requests. Results show that the coalition can always expect the similar amount of cost-savings through CTP with any tested configuration. It implies that the CTP has no conflict with the improvement of the planning techniques in reducing costs. Individual planning settings that have proved to be successful can be used for deriving proper configurations of the CTP in coalitions.

In the last test the costs of the services of common carriers are increased to an extremely high level. In this situation, a higher flexibility of the solution approach to actualize the previous plans becomes the key factor for the success of the rolling horizon planning approach and a generally smaller $\tau$-value should be chosen. Furthermore, the realized cost-savings are higher than that of Tests 2 and 3. This phenomenon implies that collaboration can better compensate the increasing prices of common carriers.

An interesting task for the future research is to study how to specify good configurations for the rolling horizon planning approaches based on different characters of instances. Another important factor is the weight function that deals with the evaluation of the information of requests offered by customers in advance. The evaluation scheme used in the conducted computational study here, especially the setting of FLP-II, has proved to be appropriate. However, in the future research, it is interesting to test more weight functions, particularly when the requests have significant different characters as in this study, including travel distances of the requests, width of time windows, as well as distribution of the lead time $t^{ld}$.

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