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„Strategic Manipulation of Bids in Auction-based Transport Collaborations"

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Abstract

It is well known that carriers could benefit from exchanging transportation requests to improve their routes. One way to enable the exchange of requests is to use an auction-based mechanism. During the auction-based mechanism, the carriers bid on each other's requests. According to their submitted bids, the requests are reallocated and the payment to and from each carrier is determined.

The purpose of this master's thesis is to evaluate how a carrier may manipulate her submitted bids to increase her profit. As the bidding strategies that a carrier could use should depend on the way her payment is determined, different payment methods are considered. The most common way to pay the carriers is by sharing the collaboration gain according to a profit-sharing method. In this thesis, five profit-sharing methods are investigated. One of those, referred to as the critical weight profit-sharing method, was, to the best of my knowledge, not proposed or tested in the literature so far and may be a promising profit-sharing method to use in practice. For all the analyzed profit-sharing methods, bidding strategies are constructed that could be used by a conspiring carrier, i.e. a carrier who knows the bids of the other carriers in advance, to increase her profit gain. Although a strategic carrier usually does not know the bids of the other carriers in advance, she should try to replicate the recommended bidding strategies as good as possible. The bidding strategies are tested on several instances and the results show that a carrier can usually significantly increase her profit gain by using her recommended strategies. In addition, the results show that the analyzed profit-sharing methods differ significantly in their robustness against the strategic manipulation of bids.

Zusammenfassung

Es ist bekannt, dass Transportunternehmen vom Austausch von Transportaufträgen profitieren könnten, um ihre Routen zu verbessern. Eine Möglichkeit, den Austausch von Transportaufträgen zu ermöglichen, besteht darin, einen auktionsbasierten Mechanismus zu verwenden. Im Rahmen des auktionsbasierten Mechanismus bieten die Transportunternehmen gegenseitig auf ihre Transportaufträge. Entsprechend ihren abgegebenen Geboten werden die Transportaufträge neu zugewiesen und die Zahlungen an und von jedem teilnehmenden Transportunternehmen werden bestimmt.

Das Ziel dieser Masterarbeit ist es, zu evaluieren, wie ein Transportunternehmen seine abgebebenen Gebote manipulieren könnte, um seinen Gewinn zu steigern. Da die Gebotsstrategien, die ein Transportunternehmen verwenden könnte, davon abhängen sollten, wie die Zahlung an und von jedem teilnehmenden Transportunternehmen bestimmt wird, werden verschiedene Zahlungsmethoden in Betracht gezogen. Die gebräuchlichste Art, die Transportunternehmen zu bezahlen, ist, den Kooperationsgewinn anhand einer Gewinnbeteiligungsmethode aufzuteilen. In der Masterarbeit werden fünf Gewinnbeteiligungsmethoden untersucht. Eine davon, die als „critical weight profit-sharing method“ bezeichnet wird, wurde meines Wissens in der Literatur bisher weder vorgeschlagen noch getestet und könnte eine vielversprechende Gewinnbeteiligungsmethode sein. Für die analysierten Gewinnbeteiligungsmethoden werden Gebotsstrategien konstruiert, die von einem Transportunternehmen, welches die Gebote der anderen Transportunternehmen im Voraus kennt, gewinnbringend genutzt werden könnten. Ein Transportunternehmen, welches die Gebote der anderen Transportunternehmen nicht im Voraus kennt, sollte versuchen, die empfohlenen Gebotsstrategien so gut wie möglich nachzubilden. Die Gebotsstrategien werden an mehreren Instanzen getestet und die Ergebnisse zeigen, dass ein Transportunternehmen sein Gewinn durch die Verwendung der empfohlenen Strategien in der Regel erheblich steigern kann. Darüber hinaus zeigen die Ergebnisse, dass die analysierten Gewinnbeteiligungsmethoden unterschiedlich robust gegen die Manipulation von Geboten sind.

Contents

List of Abbreviations

CWPM:	Critical Weight Profit-Sharing Method
EPM:	Egalitarian Profit-Sharing Method
FTL:	Full-Truckload
LTL:	Less-Than-Truckload
MEPM:	Modified Egalitarian Profit-Sharing Method
NIC:	Non-Incentive-Compatible
PSPM:	Purchase and Sale Weighted Profit-Sharing Method
ROP:	Routing Optimization Problem
SVPM:	Shapley Value Profit-Sharing Method
VCG:	Vickrey-Clarke-Groves
WDP:	Winner Determination Problem

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1 Introduction

In the recent years, many research papers were published that investigate horizontal collaborations in logistics. Essentially, horizontal collaborations are formed by companies on the same supply chain level who cooperate to increase their efficiency. In this thesis, we focus on horizontal collaborations of carriers. Carriers are usually referred to as the companies in charge of fulfilling transportation requests, whereat a transportation request can be thought of as a pickup delivery request comprising a location where an item needs to be picked up and a location to which the item needs to be delivered. The carriers need to solve routing problems to fulfill the requests, which, depending on the objectives, can be very complex. The basic idea behind a horizontal collaboration of carriers is that the carriers could increase their total efficiency by coordinating and exchanging requests to improve their routes.

A visual example of how a collaboration of carriers could increase the efficiency of their routes can be seen by comparing Figure 1 and Figure 2. Figure 1 shows the optimal routes of carriers A, B and C, if they don't trade requests.

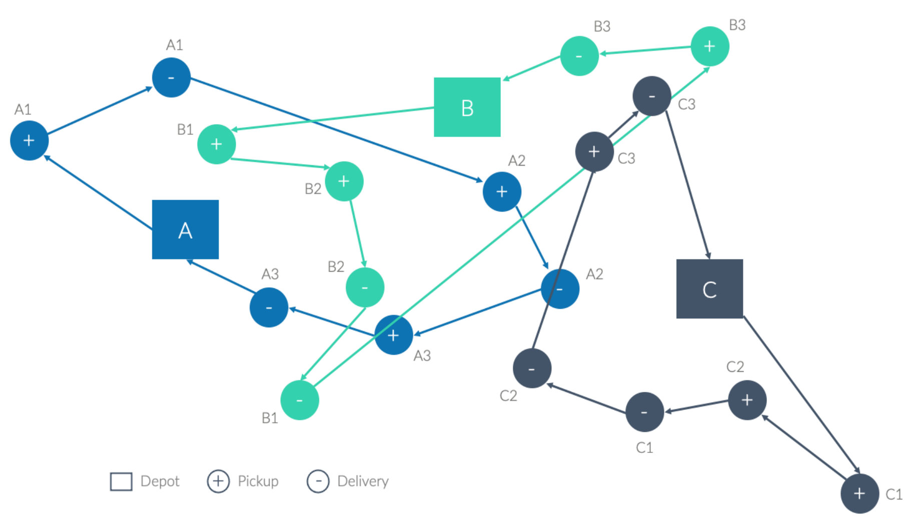

Figure 1: Routes of carriers A, B, and C before they exchanged requests

Figure 2 shows how the carriers' routes could look like, if the carriers traded the requests A2, B1, B2 and C3. Clearly, the reallocation of the requests improved the routes significantly.

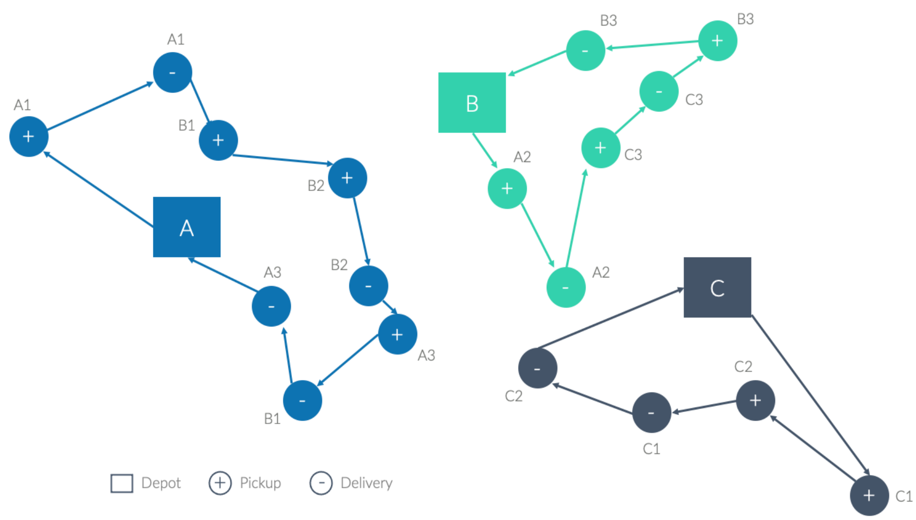

Figure 2: Routes of carriers A, B, and C after they exchanged requests

Since the transportation industry is known to be very competitive and the pressure to improve profitability is high, delivery efficiency is of outmost importance (Gansterer and Hartl, 2018b). Especially, small and medium-sized carriers, who generate only low economies of scope, could benefit from optimizing their routes by forming collaborations (Song and Regan, 2003). Research suggests that horizontal collaborations could improve the profits of all participating carriers by 20-30% (e.g., Gansterer and Hartl, 2018b; Cruijssen et al., 2007). In addition, efficiency gains in transportation may positively impact sustainability objectives like traffic, noise and pollution reduction. For example, Ballat and Fontane (2010) come to the result that collaborating supply chain members could reduce CO2 emissions by at least 25%. Hence, transport collaborations are also important for the whole of society and their support should be considered by governmental institutions. However, carriers often refuse to participate in horizontal collaborations (Sheffi, 2013). Hence, the challenge of implementing a transport collaboration that incentivizes the carriers to participate remains topic of ongoing research.

One way to implement a transport collaboration is to use an auction-based mechanism where carriers buy and sell requests. Berger and Bierwirth (2010) provide a general framework for such an auction-based mechanism. Their framework comprises 5-phases:

1. **Request Selection:** The carriers select the transportation requests that they would like to offer to the other carriers.
2. **Bundling:** The offered requests are composed to bundles
3. **Bidding:** The carriers bid on the offered bundles
4. **Winner Determination:** The best bids are selected, and the requests are allocated according to the selected bids
5. **Payment Calculation:** The payment to and from each carrier is determined

All the five phases bear challenges that are topic of ongoing research. One challenge is that the carriers might act strategically and manipulate their bids on the traded requests during the bidding phase. However, the research on strategic behavior for auction-based transport collaborations is still limited, and most research papers just assume that the carriers act truthfully (e.g. Krajewska and Kopfer, 2006; Berger and Bierwirth, 2010).

The goal of this thesis is to challenge the assumption of truthful behavior and evaluate bidding strategies that a carrier may use to manipulate her bids during the bidding phase of the auction-based mechanism to increase her profit. As the bidding strategies that a carrier could use should depend on the way her payment is calculated, different payment methods are considered[1]. The most common way to pay the carriers is by sharing the collaboration gain according to a profit-sharing method. Hence, the thesis evaluates five of the most applied and promising profit-sharing methods[2] by constructing and testing bidding strategies for each of them. One of those, referred to as the critical weight profit-sharing method, was, to the best of my knowledge, not proposed or tested in the literature so far and may be a promising profit-sharing method to use in practice. In general, the thesis gives evidence that the strategic manipulation of bids is a very important concern, and it explains how a carrier could manipulate her bids to increase her profit, dependent on the profit-sharing method used. As a result, the thesis also gives insight how robust the analyzed profit-sharing payment methods are against the strategic manipulation of bids.

[1] The payment calculation approaches are explained in Chapter 5
[2] The selected profit-sharing methods are explained in Chapter 6

The thesis is structured as follows. In Chapter 2 important classifications for the literature on horizontal transportation collaborations are explained to narrow down the research area of the thesis and introduce the research question. Afterwards, in Chapter 3, the carriers' individual objectives and challenges are introduced. In Chapter 4, the auction-based mechanism to exchange requests between the carriers is explained. In Chapter 5, different approaches to determine the carriers' payments are investigated. The famous incentive-compatible Vickrey-Clarke-Groves (VCG) payment is constructed, and it is explained why the VCG payment is usually considered impracticable. Also, a more practicable payment approach is explained, which is based on sharing the collaboration gain between the carriers. In Chapter 6, different profit-sharing methods to share the collaboration gain are introduced. Afterwards, in Chapter 7, it is investigated how a carrier could manipulate her bids to increase her profit, dependent on the profit-sharing method used. In Chapter 8, the results of the computational study to test the constructed bidding strategies are presented. Finally, Chapter 9 gives an overview of the gained insights.

2 Classifications and Research Question

The goal of this chapter is to explain important classifications for the literature on horizontal transportation collaborations to narrow down the research area of the thesis. In addition, the research gap and the research question are clarified. For a broad overview of the literature on horizontal collaborations, please also be referred to Verdonck et al. (2013), Gansterer and Hartl (2018b) and Cruijssen et al. (2007).

2.1 Classifications

The existing literature on horizontal transport collaborations can be divided in several areas of research. To get a clear picture of the existing literature, important classifications are described in the following.

Carriers vs. Shippers. Carriers should be distinguished from shippers. Usually, shippers supply the freight, while carriers plan the routes and fulfill the collected transportation requests (Liu et al., 2010). Like carriers, also shippers may profit from forming horizontal collaborations by bundling requests or lanes to improve the offered rates (Ergun et al., 2007b). Also, vertical collaborations between shippers and carriers are conceivable (Ergun et al., 2007a). Although carrier and shipper collaborations both aim to improve the routing solutions by reallocating the transportation requests, their collaboration mechanisms should be distinguished as they tend to have access to different levels of information and incentives (Gansterer and Hartl, 2018b).

Less-than-truckload vs. Full-truckload Routing Problems. The routing problem of a carrier may comprise less-than-truckload (LTL) or full-truckload (FTL) shipments. The difference is that FTL shipments can only be transported one at a time, while LTL shipments may be transported simultaneously on the same vehicle. LTL routing problems are often modeled as vehicle routing problems with pickups and deliveries (e.g., Parragh et al., 2008), while FTL routing problems are often modeled as lane covering problems (e.g., Ergun et al., 2007a). In the literature, some research papers focus on LTL transport collaborations (e.g., Gansterer et al., 2017; Dai and Chen, 2012a; Nadarajah and Bookbinder, 2013), while others focus on FTL transport collaborations (e.g., Özener et al., 2011; Liu et al., 2010).

Dynamic vs. Static settings. In dynamic environments, the carriers receive the transportation requests from their customers over time (e.g. Dai and Chen, 2011; Figliozzi, 2006; Dahl and Derigs, 2011). For example, Dai and Chen (2011) propose a dynamic multi-agent framework based on multiple iterative auctions of single requests running in parallel. Figliozzi (2006) focus on a dynamic setting where carriers randomly receive requests from their customers. He proposes an incentive compatible mechanism which, essentially, is based on the implementation of a second price auction for each incoming request. However, most research papers focus on static environments (e.g., Berger and Bierwirth, 2010; Krajewska and Kopfer, 2006) In a static environment, the carriers know all the requests from the start, and the inflow of additional requests is not considered.

Centralized vs Decentralized Planning Approaches. Transport collaborations can be categorized in collaborations with centralized planning approaches and collaborations with decentralized planning approaches (e.g., Verdonck et al., 2013; Cruijssen et al., 2007).

In centralized planning approaches, the reallocation of the transportation requests between the carriers is managed by a central authority (e.g., Dai and Chen, 2012a; Gansterer et al., 2018; Ergun et al., 2007b; Krajewska et al., 2008). The central authority optimizes the joint routing solution for all the collaborating carriers. In the case of LTL shipments, the central authority typically solves a multi vehicle pickup and delivery problem (Lu and Dessouky, 2004). In addition, some constraints may be considered, for example, maintaining a minimum number of requests per carrier, reserving customer requests that should be self-fulfilled, and keeping an even distribution of workload to ensure that all carriers are treated fairly (e.g., Gansterer et al., 2017; Schönberger, 2005). The problem with that approach is that the central authority needs to be informed about the requests and resources of the carriers to determine the optimal joint routing solution. Since the carriers are competitors, it is reasonable to assume that they do not want to share their private business information with another entity. Hence, centralized planning approaches are less likely to be implemented in practice. In the literature, centralized planning approaches are sometimes used to determine a benchmark to evaluate decentralized planning approaches (e.g., Berger and Bierwirth, 2010, Dai and Chen, 2011).

In decentralized planning approaches, the carriers do not need to share their private information with a central authority. Essentially, each carrier remains in charge of solving their routing problems, but they get access to a mechanism to exchange requests. Decentralized planning approaches can be further classified into exchange mechanisms without using auctions and auction-based mechanisms (Gansterer and Hartl, 2018b). Decentralized mechanisms without using auctions tend to be less complex. However, the carriers cannot elicit their preferences properly, which may lead to less efficiency gains (Gansterer and Hartl, 2018b). In auction-based mechanisms, carriers submit bids on the traded requests. Based on the submitted bids, the mechanism determines the allocation of the requests and the payments to and from the carriers. Auction-based mechanisms help carriers to elicit their preferences more precisely, and therefore may lead to better solutions. Several auction-based mechanisms are investigated in the literature (e.g., Krajeweska and Kopfer, 2006; Song and Regan, 2003). Since the carriers often experience significant synergies for combining requests due to economies of scope, offering requests in bundles, compared to offering them individually, can help the carriers to elicit their preferences (de Vries and Vohra, 2003). Hence, in auction-based transport collaborations, the offered requests are often combined and offered as bundles (e.g., Sheffi, 2004; Song and Regan, 2005; Ledyard et al., 2002).

2.2 Research Question

This thesis is part of the research that investigates the implementation of decentralized auction-based transport collaborations in which carriers trade LTL pickup-delivery requests in a static environment. In particular, the thesis focuses on the auction-based mechanism proposed by Berger and Bierwirth (2010), which consists of 5 phases, namely the request selection, bundle generation, bidding, winner determination and payment calculation phase, as listed in the introduction.

In the literature, one common assumption is that the carriers of a transport collaboration act truthfully (e.g., Krajewska and Kopfer, 2006; Berger and Bierwirth, 2010). However, strategic behavior may be an important consideration. In particular, the carriers may act strategically during the request selection and bidding phase. Gansterer and Hartl (2021) give evidence that the carriers are incentivized to act cooperatively during the request selection phase if the payment method considers the contributions of the carriers to the collaboration gain. However, the question remains, whether strategic behavior may be a concern during the bidding phase.

If the auction only considers single requests, and not bundles thereof, the Vickrey Auction, sometimes also referred to as the second-price auction, could be used to ensure incentive compatibility, i.e. to ensure that bidding truthfully is the optimal strategy (Vickrey, 1961). However, in a combinatorial setting, the design of an incentive compatible mechanism requires the violation of other desirable properties[3], like individual rationality, budged balance, and efficiency (Gansterer et al., 2019). Therefore, the mechanisms used in the literature are usually not incentive compatible.

The literature on strategic behavior during the bidding phase is limited. Gansterer and Hartl (2018a) come to the result that overbidding on the offered bundles leaves the cheating bidding worse off, and Jacob and Buer (2016) give evidence that underbidding on the offered bundles can increase the profit of the cheating bidder. Both use a profit-sharing method that pays the carriers an equal share of the reported collaboration gain. Strategic behavior for other profit-sharing methods were, to the best of my knowledge,

[3] The desirable properties are explained in Section 5.1

not investigated so far. Hence, investigating strategic behavior during the bidding phase for various profit-sharing methods fills a research gap.

This thesis investigates the research question whether and how carriers could manipulate their bids during the bidding phase auf the auction-based mechanism to gain more profit.

3 Preliminaries

In this chapter, the objectives of a carrier are defined. In addition, the carrier's routing problem is modeled, and her routing solution approaches are explained. This chapter is a prerequisite for understanding the processes behind horizontal carrier collaborations.

3.1 The Carriers' Objectives

It is assumed that a carrier solely wants to maximize her profit, other objectives are not considered. In other words, it is assumed that a carrier's utility equals her profit. Although this assumption seems self-evident, it is important to note that a carrier could have long-term business objectives that may be more important than maximizing her profit short-term. For example, consider the phenomenon of predatory pricing where a company offers unprofitable low prices short-term to defeat the competition (Bolton et al., 1999). However, in general, profit maximization is a reasonable objective. Therefore, it is important to determine the profit function of a carrier. For this thesis, the profit is determined like in Berger and Bierwirth (2010).

3.1.1 Profit Determination

Suppose that the revenues of a carrier emerge from the shippers' payments for the fulfillment of the transportation requests R. Each transportation request $i \in R$ comprises a pickup and delivery location. The revenue r_i for each request i comprises a fixed revenue r_f and a variable revenue $r_v(d) = \lambda d$ that depends on the direct distance d_i between the respective pickup and delivery location and a constant λ. Hence, r_i is defined by

$$r_i = r_f + r_v(d_i) \tag{3.1.1.1}$$

And the total revenue of a carrier is calculated as follows

$$Rev = \sum_{i \in R} r_i \tag{3.1.1.2}$$

To calculate the profit, we also need to consider the costs. The costs of a carrier comprise a fixed cost c_f for each request and a variable cost $C_v(D) = \mu D$ which depends on the distance D of the route to fulfill the requests and a constant μ. Hence, the total costs are defined by

$$Cost = \sum_{i \in R} c_f + C_v(D) \tag{3.1.1.3}$$

And the total profit of a carrier is calculated as follows

$$\begin{aligned} Prof &= Rev - Cost \\ &= \sum_{i \in R}(r_i - c_f) - C_v(D) \end{aligned} \tag{3.1.1.4}$$

Interestingly, the carrier can only increase her profit by reducing the distance D of the route because the other variables cannot be manipulated by her. Hence, the carrier's challenge is to find the routing solution with the shortest distance.

3.1.2 Request Evaluation

Notably, the revenue of a single request is defined by (3.1.1.1), but the costs of a single request are not defined. This is a problem because, looking ahead, a carrier may need to evaluate a single request or a bundle of requests. In the literature, the value of a set of requests is usually determined by the revenue of the requests subtracted by the costs due to the route's increase in distance to fulfill them, i.e. the requests' marginal profit (e.g., Schwind et al., 2009; Gansterer and Hartl, 2016).

Suppose that a carrier needs to evaluate a set of new transportation requests R^{new} and that the distance of the route after considering R^{new} is D′. Then the carrier's marginal profit $\varrho(R^{new})$ for R^{new} is calculated as follows

$$\varrho(R^{new}) = \sum_{i \in R^{new}}[r_i - c_f] - C_v(\Delta_D) \tag{3.1.2.1}$$

Where $\Delta_D = D' - D$

The optimal distance D' of the updated routing problem is usually hard to compute. Hence, the evaluation of a set of new transportation requests is usually computational challenging.

Evaluating the marginal profit of a set of existing requests $R^{ex} \subset R$ works likewise. However, in that case, the distance D'' of the route after excluding the requests needs to be considered. The marginal distance Δ_D is then $\Delta_D = D - D''$.

3.2 The Routing Problem

As established above, to increase her profit, a carrier needs to find the most efficient route to fulfill all her requests. The carrier's routing problem is modeled in the following. The chosen model resembles a simplified version of the single vehicle routing problem with pickups and deliveries modeled by Parragh et al. (2008).

Assume that the carrier operates a single vehicle and needs to fulfill n LTL transportation requests, where each request consists of a pickup location $i \in P$ and a delivery location $n + i \in D$. Then her routing problem can be modeled as a complete digraph $G = (V, E)$ with the vertices V and the edges E. The vertices V comprise the pickup locations $P = \{1, \dots, n\}$, the delivery locations $D = \{n + 1, \dots, 2n\}$ and the location of her depot 0, and the edges E comprise all connections (i, j) between two vertices $i \in V$ and $j \in V$.

Essentially, the carrier's decision problem is to decide which edges E to travers. The decision whether to traverse an edge $(i, j) \in E$ is modeled as a binary variable x_{ij} with $x_{ij} = 1$ if the edge (i, j) is traversed and $x_{ij} = 0$ otherwise. The distance of an edge $(i, j) \in E$ is measured by d_{ij}. For convenience, the set of edges E is reduced to the set $E' = \{(i, j) : (i, j) \in E, i \neq j\}$ to prevent that an edge can leave and directly reenter the same vertex. To keep the routing problem simple, capacity constraints, time windows, multi-depots, and other constraints are not considered. The routing optimization problem (ROP) is modeled as follows.

$$min \sum_{(i,j)\in E'} d_{ij}x_{ij} \quad (0)$$

subject to

$$\sum_{i:(i,j)\in E'} x_{ij} = 1 \quad \forall j \in V \quad (1)$$

$$\sum_{j:(i,j)\in E'} x_{ij} = 1 \quad \forall i \in V \quad (2)$$

$$B_j > B_i x_{ij} \quad \forall i \in V \setminus \{0\}, j \in V \setminus \{0\} \quad (3)$$

$$B_i < B_{n+i} \quad \forall i \in P \quad (4)$$

$$x_{ij} \in \{0,1\} \quad \forall i \in V,\ j \in V \quad (5)$$

$$B_i \in \mathbb{N} \quad \forall i \in V \setminus \{0\} \quad (6)$$

Optimization Problem 1: Routing Optimization Problem (ROP)

The optimization problem ROP resembles an integer programming problem. The objective function (0) minimizes the total distance of the routing solution. In addition, the program considers constraints (1-6). Constraint (1) ensures that each vertex is entered, and constraint (2) ensures that each vertex is left. So, constraints (1-2) ensure that each vertex $i \in (D \cup P \cup \{0\})$ is part of the routing solution. In other words, constraints (1-2) ensure that all pickup locations, delivery locations and the depot are visited. In addition, an index variable B_i for each vertex $i \in V \setminus \{0\}$, i.e. for each vertex besides the depot, is introduced to capture the order of the route. The order of the indices B_i correspond to the order of the route because constraint (3) ensures that if vertex i is visited before vertex j, B_i needs to be smaller than B_j. Constraint (3) also ensures that the route covers all vertices on one tour and not on multiple disjoint tours, which is also often referred to as sub-tour elimination. Constraint (4) enforces that every pickup location $i \in P$ needs to be visited before its respective delivery location $n + i \in D$. Constraints (5-6) define the decision variables x_{ij} and B_i.

3.3 The Routing Solution Approaches

ROP is an extended version of the traveling salesman problem, which is known to be NP-complete (Garey and Johnson, 1979; Karp, 1972). Hence, finding the optimal solution for ROP is essentially computational intractable. This is problematic as the evaluation of a set of requests according to (3.1.2.1) requires finding the distance of the updated route that includes or excludes the set of requests for evaluation. Hence, if the carrier needs to evaluate multiple set of requests, as is usually the case in transport collaborations, finding the true marginal profit for each set of requests may be impossible to compute in a reasonable amount of time.

Berger and Bierwirth (2010) solve the carriers' routing problems to optimality by using the branch and cut algorithm proposed by Dumitrescu et al. (2010). However, in their setting, each carrier initially only holds three transportation requests, which is not realistic in practice. Gansterer and Hartl (2016) give evidence that enforcing exact routing solutions is not necessary. They implement a routing heuristic with high quality results and significantly lower run times compared to Berger and Bierwirth (2010). In addition, Gansterer et al. (2020) provide a comprehensive analysis of the performance of various routing heuristics, and they come to result that, in the case of single vehicle routing problems, using simple heuristics is preferable to more complex and time-consuming metaheuristics. They propose that the carrier should use a routing heuristic that is based on the double insertion heuristic proposed by Renaud et al. (2000) and the 3-opt algorithm proposed by Lin (1965), which is also used for the conducted tests in this thesis[4]. In addition, if the carrier already determined a route, she could use the existing route to insert or delete requests without solving her routing problem from scratch. Hence, for the conducted tests in this thesis, the routing solution is only determined once from scratch. Afterwards, the requests are inserted or deleted in the carrier's existing routing solution[5].

4 Implementation of the Auction-based Mechanism

In this chapter, the implementation of the auction-based mechanism to exchange requests between the carriers is explained. The general design of the auction-based mechanism is based on the framework proposed by Berger and Bierwirth (2010), and consists of 5 phases, namely the request selection, bundle generation, bidding, winner determination and payment calculation phase, like illustrated in Figure 3.

[4] A full explanation of the implemented heuristic for initial routing solution can be found in the Appendices

[5] A full explanation of the implemented heuristics for inserting/deleting requests can be found in the Appendices

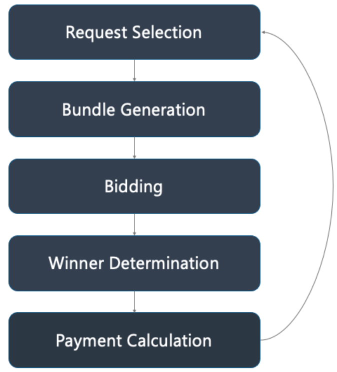

Figure 3: Illustration of the 5-phases of the auction-based mechanism

Before explaining the implementation of each phase, it is important to clarify that for this thesis it is assumed that the requests are exchanged together with their associated revenue. In some other research papers, the requests are traded as a service where the request's revenue is not part of the exchange (e.g., Schwind, 2009; Buer, 2014).

4.1 Request Selection

First, each carrier needs to decide which requests to offer. One simple approach would be to suggest that the carriers just offer all their requests to the collaboration, like assumed by Wang and Kopfer (2014). However, this assumption is not realistic in practice. Carriers may want to serve some customers themselves, or they may even be legally obliged to not share certain requests. In addition, if too many requests are submitted, then, dependent on the chosen implementation, the subsequent phases of the mechanism could become computationally intractable. Therefore, most auction-based mechanisms limit the number of requests that can be selected, and the carriers must decide which subset of requests they would like offer (e.g., Gansterer and Hartl, 2018a).

Intuitively, the carriers may decide to just offer their least profitable requests. In some research papers, it is even assumed that the carriers only offer non-profitable requests (e.g., Dai and Chen, 2011; Song and Regan, 2003). The problem with that approach is that the carrier's unprofitable requests could likely be unprofitable for the other carriers as well. Gansterer and Hartl (2016) give evidence that the transport collaboration achieves considerably higher efficiency gains if the carriers do not only offer their least valuable requests but also try to consider the value that their offered requests may have for the other carriers. Furthermore, Gansterer and Hartl (2021) give evidence that each carrier is incentivized to offer requests that are valuable for the other carriers.

For the conducted tests in Chapter 8, the request selection strategy “combo_neigh” proposed by Gansterer and Hartl (2016) is used. For a formal definition, please be referred to Gansterer and Hartl (2016). Simply put, “combo_neigh” selects a request that is far from the carrier’s own depot, close to another carrier’s depot, and not very profitable. The remaining requests are selected based on their closeness to the initially selected request. Hence, a carrier does not just select her least profitable requests in the conducted tests.

As an important sidenote, when the carrier submits her offered requests to the mechanism, she needs to update her routing solution immediately. She should update her routing solution by deleting her offered requests from the existing routing solution. This is very important because otherwise, during the subsequent bidding phase, she may falsely evaluate the other carriers’ requests based on her routing solution which still includes her offered requests.

4.2 Bundle Generation

After all the requests that the carriers would like to offer are collected, the question is how to reallocate the collected requests. One approach would be to sell each request separately. For example, Berger and Bierwirth (2010) investigate a single request assignment where each request is assigned individually through a second price auction.

The problem of that approach is that assigning the requests separately disregards the synergies between them, which leads to the well-known “exposure problem” (Milgrom, 2000). Imagine a carrier that is only interested to insource requests $r1$ and $r2$ in combination, perhaps because the pickup and delivery locations of the requests are very close to each other. If the requests $r1$ and $r2$ are sold separately, the carrier is exposed to the risk of winning only one of the requests. To solve that problem, $r1$ and $r2$ could have been offered as a bundle so that the carrier could have directly bid on both requests.

The problem is that offering all possible request bundles for n number of requests leads to $2^n - 1$ non-empty request bundles. Hence, the number of possible bundles grows exponentially with the number of offered requests. Just 30 requests would already lead to more than one billion possible bundles. This is a major problem because it is inconceivable that the carriers will be able to evaluate all possible bundles. Hence, the number of offered bundles should be reduced to a set of attractive bundles, which is also referred to as the bundle generation problem (Gansterer et al., 2020).

One important consideration is whether the bundles should be generated by the mechanism itself or by the carriers. Many research papers assume that the carriers decide which bundles to bid on (e.g., Wang and Xia, 2005; Buer, 2014). The problem of that approach is that the carriers may submit bundles that are expensive, or even impossible, to combine to a feasible request assignment (Gansterer and Hartl, 2018a). Gansterer et al. (2020) give evidence that if the bundle generation is performed by the mechanism itself, the collaboration gain is significantly higher. To decide which bundles to offer, Gansterer and Hartl (2018a) propose a genetic algorithm that considers three geographical factors, namely the isolation, density, and tour length of the bundles, to evaluate the fitness of a set of bundles.

In practice, it would be recommended to use the genetic algorithm of Gansterer and Hartl (2018a) and offer a set of attractive bundles to the carriers. However, for the conducted tests in Chapter 8, all bundles are offered. This increases the computational burden, but it has the benefit that the results of the thesis are not dependent on the implementation of the genetic algorithm.

4.3 Bidding

After the request bundles are generated, the bundles are offered to the carriers through an auction. Hence, the carriers need to submit their bids for the offered bundles.

Before deciding what to bid, a carrier usually needs to determine her true valuations for the offered bundles. Since it is assumed that the requests are traded with their associated revenue, a carrier should estimate her value for a bundle by calculating her marginal profit for the bundle's requests according to (3.1.2.1). To calculate the marginal profit, a carrier needs to evaluate the marginal distance of inserting the bundle's requests into her existing route. This is the most computational challenging part of the mechanism because each carrier needs to evaluate the set of requests for each offered bundle.

If the carriers bid truthfully, they will submit their true valuations for the offered bundles. In fact, in most research papers, it is assumed that the carriers bid their true valuations (e.g., Berger and Bierwirth, 2010; Krajewska and Kopfer, 2006). However, a carrier should investigate whether it may be beneficial to submit bids that deviate from her true valuations. This is not trivial. The bidding strategies that the carrier may use to manipulate her bids are constructed in Chapter 7. For the conducted tests in Chapter 8, various bidding strategies are tested.

4.4 Winner Determination

After all bids are collected, the mechanism needs to determine how the bundles are allocated to the carriers. The mechanism's objective is to select a feasible set of bids such that the sum of the selected bids is as high as possible. This is often referred to as the winner determination problem or combinatorial auction problem (e.g., de Vries and Vohra 2003).

Consider the grand coalition C of carriers. During the request selection phase, the requests R_C were collected from the carriers in C. Afterwards, during the bundle generation phase, the offered requests R_C were combined to the bundles T_C. Suppose that T_C also includes the empty bundle. In addition, suppose that the offered requests $R_C^i \subseteq R_C$ of each carrier $i \in C$ are always offered as a bundle, also referred to as the input bundle of carrier i. To indicate whether a request $r \in R_C$ is part of the bundle $k \in T_C$, a binary variable a_{rk} is introduced with $a_{rk} = 1$ if the request r is part of the bundle k and $a_{rk} = 0$ otherwise. During the bidding phase, each carrier i submitted the bid vector $\boldsymbol{b}_i$ with her bids b_{ik} for each bundle k. The decision whether to allocate bundle k to carrier i is modeled as a binary variable x_{ik} with $x_{ik} = 1$ if carrier i is allocated the bundle k and $x_{ik} = 0$ otherwise. The winner determination problem (WDP) is formulated as follows.

$$Z(C) = max \sum_{i \in C} \sum_{k \in T_C} b_{ik} x_{ik} \tag{0}$$

subject to

$$\sum_{k \in T_C} x_{ik} = 1 \qquad \forall i \in C \tag{1}$$

$$\sum_{i \in C} \sum_{k \in T_C} a_{rk}\, x_{ik} = 1 \qquad \forall r \in R_C \tag{2}$$

$$x_{ik} \in \{0,1\} \qquad \forall i \in C,\ k \in T_C \tag{3}$$

Optimization Problem 2: Winner Determination Problem (WDP)

The objective function (0) maximizes the total valuation of the bids on the bundles that are allocated to the carriers. In addition, WDP considers the constraints (1-3). Constraint

(1) ensures that every carrier is allocated exactly one bundle. However, note that T_C also includes the empty bundle. Therefore, constraint (1) does not prevent that a carrier may receive no request. Constraint (2) ensures that every request is allocated to exactly one carrier. Thus, constraint (2) also prevents that the same bundle or request is allocated more than once. Constraint (3) defines the decision variables x_{ik}.

In general, WDP may not have a feasible solution if not all bundles are offered. However, since it is assumed that the input bundles of the carriers are always part of the offered bundles, allocating the input bundles back to their original owners is always a feasible solution.

Notably, $Z(C)$ is dependent on the coalition of carriers. The coalition C is the grand coalition that includes all collaborating carriers. However, in the subsequent chapters, often only a sub-coalition of carriers $S \subset C$ should be considered. To calculate $Z(S)$ for a sub-coalition S, note that WDP also only considers the sub-coalition' bids, offered requests $R_S \subseteq R_C$ and bundles $T_S \subseteq T_C$ where all bundles $k \in T_S$ are composed of the requests R_S.

For convenience, the selected bid b_{ik} for a carrier i in the optimal allocation of the coalition $S \subseteq C$ is also referred to as the carrier's winning bid w_i(S). In other words, carrier i's winning bid w_i(S) is the bid b_{ik} if the bid's associated bundle k is allocated to carrier i in the optimal allocation of the coalition S. By definition, the sum of the winning bids is the value of the coalition's optimal allocation, i.e. $Z(S) = \sum_{i \in S} w_i\,(S)$.

Usually, the winner determination problem of a combinatorial auction is modeled as set packing problem (de Vries and Vohra, 2003). However, for transport collaborations, it is important that each request is allocated because otherwise it would be unclear how the, potentially unprofitable, set of remaining requests should be fulfilled. Hence, WDP is modeled as a set partitioning problem. If the requests are traded without their associated revenue, then changing the optimization program to a set covering problem may be reasonable (Buer and Pankratz, 2010). Either way, the winner determination program is NP-complete. However, the computation of WDP only needs to be conducted once for each iteration of the mechanism. Hence, in practice, solving WDP is far less computational challenging than calculating the carriers' valuations for the offered bundles.

4.5 Payment Calculation and Termination Condition

After WDP determined how the bundles should be allocated, the payments to and from each carrier need to be calculated. Intuitively, a carrier should be paid for the requests that she offered and pay for the requests that are allocated to her. However, defining the exact payment is not trivial, and several trade-offs need to be considered. In addition, the definition of the payment influences whether and how strategic carriers can manipulate their bids to increase their profit. Hence, various approaches to define the payment are explained in Chapter 5.

After the requests are allocated and the payments are disbursed, the mechanism needs to decide whether to terminate or go back to the request selection phase and conduct one more iteration. Usually, the mechanism only goes back to the request selection phase, if the carriers were able to successfully exchange requests, i.e. if the optimal allocation did not reallocate the input bundles back to their original owners (e.g., Berger and Bierwirth, 2010). However, Gansterer and Hartl (2016) give evidence that the mechanism should retry one more round before termination by collecting the carriers' second-best set of requests during the request selection phase. Hence, for the conducted tests in Chapter 8, it is implemented that the mechanism retries one more round before termination.

5 Payment Calculation Approaches

In this chapter, different approaches to calculate the payments for the carriers are introduced. Depending on which payment method is used, the properties of the mechanism change significantly. Hence, to evaluate the payment methods, it is important to first define the desirable properties of the mechanism. Afterwards, two classes of payment methods are investigated, namely incentive-compatible payments and non-incentive compatible payments.

5.1 Desirable Properties

In the literature, often the properties efficiency, incentive compatibility, individual rationality, and budget balance are desired (e.g., Gansterer et al., 2019; Xu et al., 2017).

Efficiency. Efficiency means that the social welfare of the participants of the mechanism is maximized (Nisan et al., 2007). In a single item auction, an efficient mechanism would always select the bidder with the highest valuation for the offered item. For more complex settings, it makes sense to think about an efficient mechanism as a mechanism where, after termination, no trades are possible that could increase the profit gains for the participants (Wurman et al., 1998).

Incentive Compatibility. Incentive compatibility ensures that every participant of the mechanism is incentivized to act truthfully. More precisely, the mechanism ensures that acting truthfully is a dominant strategy or at least leads to a Bayesian-Nash equilibrium (Nisan et al., 2007). For auctions, incentive compatibility guarantees that all bidders are incentivized to bid their true valuations for the offered items. As a result, the bidders do not need to worry about coming up with complex bidding strategies. Hence, incentive compatibility is also beneficial computationally (Parkes et al., 2001). In addition, constructing a mechanism that predictably maximizes the true social welfare, i.e. satisfies efficiency, usually relies on the assumption that the information supplied to the mechanism is truthful (Nisan et al., 2007).

Individual Rationality. Individual rationality guarantees that no participant is worse off after participating in the mechanism, i.e. all participants gain non-negative utility[6] from their participation in the mechanism (Xu et al., 2017). Without individual rationality, a participant may refuse to participate in the mechanism due to the risk of making a loss. In some cases, it might make sense to weaken the notion of individual rationality and allow that a participant could make a loss in the short term if she benefits from her participation in the long run (Gansterer et al., 2019).

Budget Balance. If the mechanism is budget balanced, the inflow and outflow of money during the mechanism eventually balances out. In other words, the mechanism would be self-funding and independent of an external source of funding (Hobbs et al. 2000). If the mechanism is not budget balanced, the question arises, how the remaining profit or loss is allocated among the participants, which introduces new incentive issues (Gansterer et al., 2019).

[6] We will assume that her utility equals her profit, as explained in chapter 3

Other properties. Other properties may be interesting as well. One property often mentioned, although hard to define formally, is fairness (e.g. Gansterer et al., 2020; Ackermann et al., 2011). Dahl and Derigs (2011) suggest that their implemented carrier collaboration framework failed in practice due to an unfair payment scheme. Also, computational efficiency is an interesting property. If the mechanism cannot be computed in a reasonable amount of time, it cannot scale and cannot be used in practice. As a matter of fact, the importance of addressing computational efficiency requirements lead to the emergence of a new research field referred to as "Algorithmic Mechanism Design" (Nisan and Ronen, 2001).

5.2 Incentive-Compatible Payments

Based on the previously defined desirable properties, it is reasonable to ask whether it may be possible to define the payment method such that the bidders are incentivized to bid truthfully, i.e. to ensure incentive compatibility. In that case a carrier would not be able to strategically manipulate her bids to increase her profit.

In general, is possible to ensure incentive compatibility if the payment is defined according to the Vickrey-Clarke-Groves (VCG) mechanism. The VCG mechanism builds on the work of Vickrey (1961), Clarke (1971) and Groves (1973), and is a generalization of the Vickrey auction, also referred to as second-price auction, which is a well-known incentive compatible auction for single items. In the following, the VCG payment for the auction-based mechanism is defined, and the disadvantages of using the VCG payment are explained.

5.2.1 Construction of the VCG Payment

In the literature, the VCG payment is usually constructed for combinatorial auctions where the participants only act as bidders. This is problematic because treating the carriers solely as bidders, ignores the fact that the carriers are also the offerors of the requests. Hence, the winner determination program is often remodeled as an exchange where the carriers do not bid on the offered bundles, but on packages that include their offered requests to the other carriers and their demanded requests from the other carriers (e.g., Gansterer et al., 2019; Parkes et al., 2001). However, it is also possible to use WDP to construct the VCG payment, as demonstrated in the following.

Suppose the grand coalition C of carriers where we take the perspective of an arbitrary selected carrier $c \in C$. In addition, assume the coalition $S = C\backslash\{c\}$ that includes all carriers besides carrier c. To incentivize carrier c to bid truthfully, her payment should be determined according to the Groves mechanism (Groves, 1973). The Groves payment $p_c^g(C)$ is defined as follows

$$p_c^g(C) = \sum_{j\in S} w_j(C) - h(S) \tag{5.2.1.1}$$

$$= Z(C) - w_c(C) - h(S)$$

The term $\sum_{j\in S} w_j(C)$ calculates the sum of the winning bids of the carriers $S = C\backslash\{c\}$ in the optimal allocation of the grand coalition C, and the term $h(S)$ is an arbitrary function that only depends on the sub-coalition S. Since carrier c is excluded from S, she cannot manipulate $h(S)$.

To understand why $p_c^g(C)$ incentivizes carrier c to bid truthfully, let us assume that we know carrier $c's$ true valuations v_{ck} for each bundle k $\in T_C$, i.e. her marginal profits for each bundle. In addition, suppose that carrier c's valuation for her input bundle o, i.e. her valuation of her offered requests, is v_{co}, and that in the optimal allocation, ${x^*}_{ik} = 1$ if carrier $i \in C$ is allocated bundle $k \in T_C$ and ${x^*}_{ik} = 0$ otherwise. Then carrier $c's$ profit $\pi_c(C)$ can be calculated as follows

$$\pi_c(C) = \sum_{k\in T_C} v_{ck}{x^*}_{ck} + p_c^g(C) - v_{co} \tag{5.2.1.2}$$

$$= \sum_{k\in T_C} v_{ck}{x^*}_{ck} + \left(\sum_{j\in S} w_j(C) - h(S)\right) - v_{co}$$

$$= \sum_{k\in T_C} v_{ck}{x^*}_{ck} + \left(\sum_{j\in S}\sum_{k\in T_C} b_{jk}{x^*}_{jk} - h(S)\right) - v_{co}$$

$$= \underbrace{\sum_{k\in T_C} v_{ck}{x^*}_{ck} + \sum_{j\in S}\sum_{k\in T_C} b_{jk}{x^*}_{jk}}_{\text{Influenceable term}} - h(S) - v_{co}$$

Carrier $c's$ profit $\pi_c(C)$ is determined by her marginal profit $\sum_{k\in T_C} v_{ck}{x^*}_{ck}$ for her allocated bundle and her payment $p_c^g(C)$ subtracted by her marginal profit v_{co} for her input bundle, which she gives away. Notably, she can only increase $\pi_c(C)$ by increasing the "influenceable term" as $h(S)$ and v_{co} cannot be manipulated. Interestingly, the "influenceable term" is the same as the objective function of WDP if carrier c bids her true valuations, i.e. $\boldsymbol{b}_c = \boldsymbol{v}_c$. Hence, if she submits her true valuations, WDP maximizes the "influenceable term" for her. Therefore, carrier c is incentivized to bid her true valuations[7]. As a result, $p_c^g(C)$ is incentive compatible and could be used to ensure that the bidders cannot profit from manipulating their bids.

In principle, $h(S)$ could be set to 0. However, a popular choice to calculate $h(S)$ is to use the Clarke Pivot Rule (Nisan et al., 2007). If $h(S)$ is calculated according to the Clarke Pivot Rule, the Groves payment is usually referred to as the VCG payment. The basic idea behind the Clarke Pivot Rule is to charge or pay a carrier the externalities that she imposes on the other carriers (Nisan et al., 2007). In other words, to charge or pay a carrier the damage or improvement of the other carriers' profits due to her participation in the mechanism. According to the Clarke Pivot Rule, $h^{CPR}(S)$ is defined as follows

$$\begin{aligned} h^{CPR}(S) &= \sum_{j \in S} w_j(S) \\ &= Z(S) \end{aligned} \tag{5.2.1.3}$$

Hence, $h^{CPR}(S)$ is the value of the optimal allocation according to WDP without considering the bids and requests of carrier c. The VCG payment $p_c^{vcg}(C)$ is then defined as follows

$$\begin{aligned} p_c^{VCG}(C) &= \sum_{j \in S} w_j(C) - h^{CPR}(S) \\ &= \sum_{j \in S} w_j(C) - \sum_{j \in S} w_j(S) \\ &= Z(C) - w_c(C) - Z(S) \end{aligned} \tag{5.2.1.4}$$

The VCG payment $p_c^{VCG}(C)$ is the difference between the value that the sub-coalition receives in the grand coalition's optimal allocation and the value of the sub-coalition's optimal allocation. In transport collaborations, $p_c^{VCG}(C)$ is often positive because the participation of a carrier often improves the profits of the other carriers due to the carrier's offered requests. Notably, $p_c^{VCG}(C)$ also ensures individual rationality, i.e. carrier c cannot make a loss if she is paid according to $p_c^{VCG}(C)$[8].

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[7] We assume that her profit equals her utility, as explained in Chapter 3.1.

[8] For the proof of individual rationality, please be referred to the Appendices

5.2.2 Disadvantages of the VCG Payment

The VCG payment ensures incentive compatibility and individual rationality. Hence, the carriers would not profit from manipulating their bids. In addition, since the carriers bid truthfully, efficiency is ensured because WDP can find the true optimal allocation. Nevertheless, the VCG payment is usually considered non-practical (e.g., Pekeč and Rothkopf, 2003). In the following, the disadvantages of using the VCG payment are explained.

Not Budget Balanced. The VCG payment is not budget balanced. This can be illustrated by a simple example. Suppose carriers $c1$ and $c2$. Carrier $c1$ offered request $r1$ and carrier $c2$ offered request $r2$. Their bids are listed in the Table 1.

	c1	c2
{}	0	0
{r1}	3	1
{r2}	2	4
{r1, r2}	8	7

Table 1: The bids that carriers $\boldsymbol{c1}$ and $\boldsymbol{c2}$ submitted for the offered request bundles

In the optimal allocation $c1$ wins her bid on the bundle {r1, r2} and $c2$ "wins" the empty bundle $\{\}$. According to the VCG payment $p_c^{VCG}(C)$, defined by (5.2.1.4), $c1$ gets paid $Z(C) - w_{c1}(C) - Z(C\backslash\{c1\}) = 8 - 8 - 4 = -4$, i.e. $c1$ needs to pay 4, and $c2$ gets paid $Z(C) - w_{c2}(C) - Z(C\backslash\{c2\}) = 8 - 0 - 3 = 5$. Since $c1$ pays 4 but $c2$ gets paid 5, the mechanism makes a loss of 1. Hence, budget balance is violated, and the question arises who covers the loss of the exchange.

One approach to cover the loss of the exchange would be to charge the carriers a fee based on the expected loss. However, Gansterer et al. (2019) show that using a participation fee to cover the losses leads to the violation of individual rationality in a significant number (~35-50%) of cases. To mitigate that problem, they propose a team bidder mechanism which can reduce the violations of individual rationality but not prevent it. Another interesting approach is investigated by Parkes et al. (2001). They enforce budget balance as a hard constraint and compute payments that are as close as possible to the VCG payment.

Notably, it is impossible to change the VCG payment such that budget balance is ensured without losing some of the other desirable properties. Myerson and Satterthwaite (1983) proof that no incentive compatible exchange can be individual rational, efficient, and budget balanced simultaneously.

Cheating Opportunities. The VCG payment may encourage collusion and shill bidding (e.g. Ausubel and Milgrom, 2020; Cramton et al., 2004). Essentially, the VCG payment is incentive compatible because a carrier cannot influence her own payment. The problem is that the payment can be influenced by the other carriers. Therefore, the carrier might collude with some of the other carriers. On top of that, in the case of shill bidding, the carrier might even fake the participation of other carriers to influence her payment. Rothkopf (1999) give evidence that mechanisms that are often repeated may be especially vulnerable to collusion. Since transport collaborations would likely exchange requests regularly and the underlying traded value would likely be large, collusion and shill-bidding might be a concern.

Budget Constraints. The VCG payment can only ensure incentive compatibility under the assumption that the carriers do not have any budget constraints, i.e. the money that a carrier can spend needs to be unlimited (Che and Gale, 1998). Examples of how budget constraints may break the incentive guarantees of the VCG payment can be found in the literature (e.g., Ausubel and Milgrom, 2020). It is reasonable to assume that carriers do not have unlimited funds to buy requests. In addition, carriers may not be able to include all the offered requests in their routes. Therefore, budget constraints are a relevant concern.

5.3 Non-Incentive-Compatible Payments

Since the VCG payment has several disadvantages, it is reasonable to relax the property of incentive compatibility. In the literature, the carriers are often paid a share of the collaboration gain according to a profit-sharing method, instead of the VCG payment (e.g. Berger and Bierwirth, 2010; Gansterer et al., 2020). In this section, the approach of paying the carriers a share of the collaboration gain is formulized. The resulting payment is also referred to as the non-incentive-compatible (NIC) payment.

First, it is assumed that a carrier $i \in C$ pays her bid on her allocated bundle, i.e. her winning bid $w_i(C)$, and gets paid her bid on her input bundle, which is referred to as her input bid e_i. If a carrier bids truthfully, her winning bid $w_i(C)$ will match her marginal profit of her allocated bundle and her input bid e_i will match her marginal profit of her input bundle. As a result, she would neither make a loss nor a gain from participating in the request exchange. However, if all carriers are paid their input bids and charged their winning bids, usually some profit will be left over. This profit is referred to as the collaboration gain $g(C)$ and is defined as follows

$$g(C) = \sum_{i \in C} w_i(C) - \sum_{i \in C} e_i \tag{5.3.1}$$

The collaboration gain $g(C)$ can be interpreted as the marginal profit that the coalition C was able to achieve by exchanging requests. Notably, $g(C)$ cannot be negative because if the collaboration cannot make a profit by exchanging requests, the input bundles will be allocated to their original owners and $\sum_{i \in C} w_i(C) = \sum_{i \in C} e_i$ will hold. If $g(C)$ is positive, each carrier will receive a share $g_i(C)$ of the collaboration gain. Hence, the NIC payment $p_i^{NIC}(C)$ is defined as follows

$$p_i^{NIC}(C) = e_i + g_i(C) - w_i(C) \tag{5.3.2}$$

If a carrier bids truthfully, the carrier's profit from participating in the request exchange will equal her share of the collaboration gain $g_i(C)$ as getting paid her input bid e_i would match her profit loss from offering her input bundle and paying her winning bid $w_i(C)$ would match her profit gain from receiving her allocated bundle.

The NIC payment $p_i^{NIC}(C)$ satisfies budget balance and individual rationality if $g(C) = \sum_{i \in C} g_i(C)$ and $g_i(C) \geq 0$. However, in contrast to the VCG payment, $p_i^{NIC}(C)$ cannot guarantee incentive compatibility. In addition, since the carriers may not bid truthfully, WDP might not determine the true optimal allocation. Hence, efficiency cannot be ensured either. In the literature, it is often argued that the carriers may bid truthfully anyway because the strategic manipulation of bids could be too complex (e.g., Gansterer et al., 2019). However, this should depend on the implemented profit-sharing method, i.e. the method that defines the carriers' shares of the collaboration gain $g_i(C)$. Hence, it is important to analyze various profit-sharing methods.

6 Profit-Sharing Methods

For the NIC payment, as defined by (5.3.2), it is important to determine how the collaboration gain should be shared between the carriers. Guajardo and Rönnqvist (2016) provide a comprehensive overview of various cost- and profit-sharing methods used for transport collaborations. In this chapter, five profit-sharing methods are selected and analyzed.

6.1 Egalitarian Profit-Sharing Method (EPM)

The simplest way to share the collaboration gain is to share it equally between the carriers. This is also referred to as the egalitarian profit-sharing method (EPM).

Suppose the grand coalition C where $|C|$ is the number of carriers. For an arbitrary selected carrier $c \in C$, her share of the collaboration gain $g_c^{EPM}(C)$ is calculated as follows

$$g_c^{EPM}(C) = \frac{g(C)}{|C|} \tag{6.1.1}$$

Her share of the collaboration gain $g_c^{EPM}(C)$ is easy to understand and compute. Because of its simplicity, the egalitarian profit-sharing approach is often used in the literature (e.g. Berger and Bierwirth, 2010; Gansterer and Hartl, 2018a). One major disadvantage is that it may be considered unfair because the contribution that a carrier made to increase the collaboration gain is not considered. In addition, Jacob and Buer (2018) give evidence that using the egalitarian approach may incentivize the carriers to underbid their values on the offered bundles.

6.2 Modified Egalitarian Profit-Sharing Method (MEPM)

The modified egalitarian profit-sharing method (MEPM) is very similar to EPM. However, with the modification that a carrier will only get a share of the collaboration gain if she is not allocated her input bundle, i.e. if she does not win her input bid e_c. In other words, the carrier will only get a share of the collaboration gain if her participation changes the optimal allocation of the other carriers.

Suppose the grand coalition C where a subset of carriers $C' \subseteq C$ are allocated a bundle different from their input bundle in the optimal allocation. For an arbitrary selected carrier $c \in C$, her share of the collaboration gain $g_c^{MEPM}(C)$ is calculated as follows

$$g_c^{MEPM}(C) = \frac{g(C)}{|C'|} \qquad \text{if } c \in C' \tag{6.2.1}$$
$$g_c^{MEPM}(C) = 0 \qquad \text{if } c \notin C'$$

Her share of the collaboration gain $g_c^{MEPM}(C)$ is easy to understand and compute. In contrast to EPM, MEPM seems fairer as the carriers who do not contribute to the collaboration gain won't get a share of it.

6.3 Purchase and Sale Weighted Profit-Sharing Method (PSPM)

Another approach is to share the collaboration gain between the carriers by assigning weights to them according to their contributions to the mechanism (Guajardo and Rönnqvist, 2016). Ideally, those weights would lead to an allocation that is considered fair and incentivizes contributions to the mechanism. Gansterer et al. (2020) propose using weights based on the input and winning bids of the carriers. They also refer to this method as the purchase and sale weighted profit-sharing method (PSPM).

Suppose the grand coalition C with an arbitrary selected carrier $c \in C$. Carrier c's purchase and sale weight $\varphi_c^{PSPM}(C)$ and her resulting share of the collaboration gain $g_c^{PSPM}(C)$ are calculated as follows

$$g_c^{PSPM}(C) = \varphi_c^{PSPM}(C)\mathrm{g}(C) \tag{6.3.1}$$
$$Where \;\; \varphi_c^{PSPM}(C) = \frac{1}{2}\left(\frac{|e_c|}{\sum_{i \in C}|e_i|} + \frac{|w_c(C)|}{\sum_{i \in C}|w_i(C)|}\right)$$

If carrier c bids truthfully, her input bid e_c will reflect her value of her input bundle, i.e. her sold requests, and her winning bid $w_c(C)$ will reflect her value of her allocated bundle, i.e. her purchased requests. Hence, the weight $\varphi_c^{PSPM}(C)$ will reflect carrier c's weighted average of her valuations for her sold[9] and purchased[10] requests relative to those of the

[9] i.e. the requests of her input bundle
[10] i.e. the requests of her allocated bundle

other carriers. Notably, $\varphi_c^{PSPM}(C)$ only considers absolute values to ensure that the weights are non-negative, i.e. $\varphi_i^{PSPM}(C) \geq 0$ for all carriers $i \in C$. The weights should not be negative because otherwise individual rationality would be violated for the carriers with negative weights (Gansterer et al., 2020).

Gansterer et al. (2020) argue that PSPM is superior to EPM because both methods would be easy to compute but in the case of PSPM the carriers would be incentivized to contribute to the mechanism. In addition, since the carriers' contributions are considered, PSPM seems fairer.

6.4 Shapley Value Profit-Sharing Method (SVPM)

Another way to share the collaboration gain is to use a traditional, well-studied allocation method from the literature of collaborative games. One of the most famous allocation models that could be used to share the collaboration gain is the Shapley Value, defined by Shapley (1953). In this thesis, the method of sharing the collaboration gain according to the Shapley Value is also referred as the Shapley Value profit-sharing method (SVPM).

Suppose the grand coalition C where the carriers can be joined in coalitions $S \subseteq C$. In addition, assume that $|S|$ is the number of carriers in a coalition S and $|C|$ is the number of carriers in the grand coalition C. For an arbitrary selected carrier $c \in C$, her share of the collaboration gain $g_c^{SVPM}(C)$ is calculated as follows

$$g_c^{SVPM}(C) = \sum_{S \subseteq C \setminus \{c\}} \frac{|S|!\,(|C|-|S|-1)!}{|C|!} \left[g(S \cup \{c\}) - g(S)\right] \tag{6.4.1}$$

Essentially, the Shapley Value allocates the collaboration gain $g(C)$ to the carriers according to the weighted average of their marginal contributions to the collaboration gains of all coalitions that they could be part of. Hence, the Shapley Value directly rewards contributions to the collaboration gain, which is already a nice property by itself. In addition, the Shapley Value fulfills several notable economic properties, namely budget balance[11], exclusion of dummies, symmetry, and additivity (Shapley, 1953). Some of those properties are closely related to the notion of fairness, for example, the exclusion of dummies prevents that the collaboration gain is shared with carriers that did not contribute, and symmetry ensures that if two carriers made the same contribution, they

[11] i.e. $g(C) = \sum_{i \in C} g_i^{SVPM}(C)$

would get an equal share of the collaboration gain. Hence, the Shapley Value is usually considered to be fair (e.g., Krajewska et al., 2008).

One common point of criticism is that the Shapley Value does not necessarily lay in the core, a well-known economic property that could be interpreted as group rationality (Guajardo and Rönnqvist, 2016). Simply put, a payment is in the core if it is impossible for a sub-coalition of carriers $S \subset C$ to split up from the grand coalition C to increase their payment. If the carriers do not have an incentive to split up, the grand coalition may be more stable. Hence, the Shapley Value is sometimes modified such that the payment lays in the core[12] (e.g., Dai and Chen, 2012b). For transport collaborations, the core property may not be so relevant because it is, arguably, impracticable for the carriers to figure out whether some sub-coalition may be more profitable each time they come together to exchange requests.

Another critic of the Shapley Value is that it is hard to compute (e.g., Gansterer et al., 2020). To calculate the collaboration gain $g(S)$ for a coalition $S \subseteq C$, it is necessary to solve WDP, which is NP-complete. To make things worse, the number of coalitions grows exponentially with the total number of carriers $|C|$ as it is possible to form $2^{|C|} - 2$ sub-coalitions from the grand coalition C. However, for transport collaborations, the number of collaborating carriers may not be so high. Therefore, the calculation of the Shapley Value should usually be less computationally challenging than the carriers' evaluations of the offered request bundles.

The main problem is that it is inconceivable to compute the Shapley Value accurately for transport collaborations with many requests. To calculate the Shapley Value, it is necessary to determine the collaboration gain for all possible coalitions, which assumes that each coalition can be evaluated properly. This assumption is problematic because to calculate the true collaboration gain for a coalition, it is necessary that the carriers in the coalition evaluate all the coalition's request bundles. Yet, it is usually computationally intractable to require the carriers to evaluate all possible request bundles. As explained previously, the set of all request bundles should be reduced to a set of attractive request bundles to reduce the computational workload[13]. The reduced set of attractive request bundles may be sufficient to find a near optimal allocation for the grand coalition, but it may not be sufficient to find near optimal allocations for the sub-coalitions. As a result,

[12] [12] If the core is non-empty

[13] For the conducted tests all possible bundles offered. But in practice that is inconceivable.

the true collaboration gain of each sub-coalition cannot be determined correctly, and the calculated Shapley Value becomes less accurate.

6.5 Critical Weight Profit-Sharing Method (CWPM)

Following the ideas of the Shapley Value, a profit-sharing method referred to as the critical weight profit-sharing method (CWPM) is introduced that assigns weights to the carriers based on their critical contributions to the collaboration gain. To the best of my knowledge, CWPM was not proposed or tested in the literature so far.

As explained previously, the Shapley Value allocates a share of the collaboration gain to a carrier according to the weighted average of her marginal contributions to the collaboration gains of all coalitions that she could be part of, as defined by (6.4.1). The main problem of the Shapley Value is that it is usually inconceivable to accurately calculate a carrier's marginal contribution to the collaboration gain for each sub-coalition. Following this insight, CWPM does not consider a carrier's marginal contribution for each sub-coalition, but only for the sub-coalition that includes all carriers besides herself.

Suppose the grand coalition C with an arbitrary selected carrier $c \in C$ where the sub-coalition S = $C \backslash \{c\}$ includes all carriers of C besides carrier c. In this thesis, carrier c's marginal contribution to the collaboration gain of the grand-coalition C from the sub-coalition S is also referred to as her critical contribution $\psi_c(C)$. Her critical contribution is calculated as follows

$$\psi_c(C) = g(C) - g(S) \tag{6.5.1}$$

Then, carrier c's critical weight $\varphi_c^{CWPM}(C)$, and her resulting share of the collaboration gain $g_c^{CWPM}(C)$ are calculated as follows

$$g_c^{CWPM}(C) = \varphi_c^{CWPM}(C) g(C) \tag{6.5.2}$$

$$Where\ \ \varphi_c^{CWPM}(C) = \frac{\psi_c(C)}{\sum_{i \in C} \psi_i(C)}$$

Carrier c's critical weight $\varphi_c^{CWPM}(C)$ reflects her critical contribution $\psi_c(C)$ in relation to the critical contributions of the other carriers. In contrast to the purchase and sale weight $\varphi_c^{PSPM}(C)$, the critical weight $\varphi_c^{CWPM}(C)$ is directly linked to the carrier's contribution to the collaboration gain. Like MEPM, CWPM does not share the collaboration gain with carriers that are allocated their own input bundle as their critical contribution would equal 0. As a result, CWPM should incentivize the carriers to contribute to the mechanism. In contrast to SVPM, CWPM does not require the evaluation of all sub-coalitions, which makes it easier to compute and more practicable. All in all, CWPM seems to be a promising profit-sharing method.

7 Strategic Manipulation of Bids

In this chapter, it is investigated if and how a carrier could manipulate her bids to increase her profit.

If the mechanism implements the VCG payment, defined by (5.2.1.4), a carrier, by construction, cannot increase her profit by manipulating her bids. However, as explained previously, the VCG payment is not budget balanced. Therefore, it is not possible to implement the VCG payment without introducing a method to cover the mechanism's losses, which may introduce new incentive issues. Finding an appropriate method to cover the mechanism's losses, may be a promising research topic but won't be analyzed in this thesis.

If the mechanism implements the NIC payment method, defined by (5.3.2), the carrier may increase her profit by manipulating her bids. However, the specific bidding strategies that a carrier could use should depend on the selected profit-sharing method for the NIC payment. Hence, the profit-sharing methods, which are described in the previous chapter, are analyzed separately. During the analyses, the gained insights are used to construct bidding strategies. In conclusion, the analyses should give insight about which bidding strategies a carrier may use, what kind of information may be valuable, and how robust the analyzed profit-sharing methods may be in practice.

For the strategic analyses, three types of carriers are distinguished:

Conspiring Carriers. A conspiring carrier is a carrier who knows the bids that the other carriers are going to submit during the bidding phase. This may be the case if the carrier conspires with the manager of the mechanism. A conspiring carrier constructs bidding strategies to increase her profit by using her knowledge about the other carriers' bids.

Strategic Carriers. A strategic carrier does not know the bids that the other carriers are going to submit. However, a strategic carrier evaluates how to manipulate her bids to increase her profit.

Truthful Carriers. A truthful carrier is a carrier who always bids her truthful valuations.

During the analyses, we take the perspective of a single carrier $c \in C$ who is either a conspiring or a strategic carrier. In addition, it is assumed that all the other carriers $C\backslash\{c\}$ are truthful carriers. Hence, the analyses do not predict the equilibria but evaluate how carrier c should manipulate her bids if the other carriers bid truthfully.

Initially, it is assumed that carrier c sets all her bids to her truthful valuations, i.e. $\boldsymbol{b}_c = \boldsymbol{v}_c$. Hence, her payment $p_c^{NIC}(C) = e_c + g_c(C) - w_c(C)$ would compensate her for her profit loss from offering her input bundle and charge her for her profit gain from receiving her allocated bundle. In addition, as all bidders would submit their true valuations, WDP could determine the true optimal allocation, i.e. the allocation that leads to the maximal possible true collaboration gain $g(C)$. As a result, carrier c's profit would equal her share of the true collaboration gain $g_c(C)$. From this starting point, it is analyzed how carrier c could manipulate her bids to increase her profit. Usually, she should try to increase her profit by increasing her payment $p_c^{NIC}(C)$ without changing the true optimal allocation.

First, we take the perspective of the conspiring carrier. Hence, the analyses start by answering the question how carrier c should manipulate her bids if she knows the bids of the other carriers in advance. During the analyses, various bidding strategies are constructed that increment or decrement carrier c's truthful bids so that her profit gain increases. This should help to evaluate the maximal profit gain that a carrier may receive from bidding strategically, and it gives insight about the information that may be valuable for a strategic carrier. In the next step, we take the perspective of a strategic carrier. Hence, the analyses continue by answering the question how carrier c should manipulate her bids if she does not know the bids of the other carriers in advance. The proposed strategies for the strategic carrier are usually derived from the insights of the analyses for the conspiring carrier.

7.1 Analysis for EPM

First, the egalitarian profit-sharing method is analyzed. The carrier's share of the collaboration gain is $g_c^{EPM}(C)$, as defined by (6.1.1). The according NIC payment $p_c^{EPM}(C)$ is calculated as follows

$$p_c^{EPM}(C) = e_c + \frac{g(C)}{|C|} - w_c(C) \tag{7.1.1}$$

Analysis for the Conspiring Carrier

As already explained, carrier c's profit would equal $g_c(C) = \frac{g(C)}{|C|}$. However, she could try to raise her profit by increasing her payment $p_c^{EPM}(C)$. Ceteris paribus, she could raise her payment $p_c^{EPM}(C)$ by increasing $g(C)$, increasing e_c or decreasing $w_c(C)$.

Intuitively, increasing the collaboration gain $g(C)$ is not possible because $g(C)$ would be the maximal true collaboration gain if she bid truthfully. By manipulating her bids, carrier c could try to increase the reported collaboration gain. However, to increase the reported collaboration gain, carrier c would need to either underbid on her input bid e_c or overbid on her winning bid $w_c(C)$, which would both directly decrease her payment.

Alternatively, carrier c could try to raise her payment $p_c^{EPM}(C)$ by increasing her input bid e_c. If carrier c does not win her input bid e_c, increasing e_c by Δ, will increase $p_c^{EPM}(C)$ by $\Delta - \left(\frac{g(C)}{|C|} - \frac{g(C)-\Delta}{|C|}\right) = \Delta - \frac{\Delta}{|C|}$. Clearly, $\Delta > \frac{\Delta}{|C|}$ because the number of collaborating carriers $|C|$ is greater than 1. Hence, carrier c should, in general, increase e_c by as much as possible. However, at some point, her reported input bid e_c' would be so high that she would win it, i.e. she would be allocated her input bundle. This is not in her interest. Her new profit would equal her share of the collaboration gain of the new allocation where she is allocated her input bundle, i.e. $g_c^{EPM}(C)' = \frac{g'(C)}{|C|}$. Notably, $g'(c) \leq g(c)$ as $g(c)$ is the collaboration gain of the true optimal allocation and cannot be increased by changing the allocation. Therefore, carrier c would make a loss of $\frac{g(C)}{|C|} - \frac{g'(C)}{|C|}$. Hence, it can be concluded that carrier c's strategy should be to increase her input bid e_c as much as possible but not by so much that she would win it[14]. Based on this insight, the bidding strategy *Input-Max* is introduced.

Input-Max. If carrier c is not allocated her input bundle in the true optimal allocation, she should increase her input bid e_c as much as possible but not so much that she would win it. In other words, carrier c should increase e_c up to the threshold where WDP would determine to allocate her input bundle back to her. To calculate that threshold, carrier c needs to know the value $Z(S)$ of the optimal allocation of the carriers $S = C\backslash\{c\}$, i.e. the optimal allocation without considering her bids and requests according to WDP. By knowing $Z(S)$, she knows that the best allocation where she gets back her input bundle must have the value $Z(S) + e_c$. Hence, if she increases e_c by less than $\Delta = Z(C) - (Z(S) + e_c)$, she won't be allocated her input bundle as $Z(C) > Z(S) + e_c + \Delta$. Following this insight, her optimal increment Δ_c^{IM} for e_c is calculated as follows

$$\Delta_c^{IM}(C) = Z(C) - (Z(S) + e_c) - \epsilon \quad (7.1.2)$$

Where ϵ is a very small number

Suppose that carrier c's share of the collaboration gain after increasing e_c by $\Delta_c^{IM}(C)$ is $g_c^{IM}(C)$, then her resulting marginal profit $\delta_c^{IM}(C)$ can be calculated as follows

$$\delta_c^{IM}(C) = \Delta_c^{IM}(C) - [g_c(C) - g_c^{IM}(C)] \quad (7.1.3)$$

If the collaboration gain is shared according to EPM, her marginal profit $\delta_c^{IM}(C)$ will be positive, as $[g_c(C) - g_c^{IM}(C)] = \frac{g(C)}{|C|} - \frac{g(C)-\Delta_c^{IM}(C)}{|C|} = \frac{\Delta_c^{IM}(C)}{|C|} < \Delta_c^{IM}(C)$ and $\Delta_c^{IM}(C) > 0$[15]. Notably, also for most other profit-sharing methods her marginal profit $\delta_c^{IM}(C)$ should be positive, as $[g_c(C) - g_c^{IM}(C)]$ will likely be smaller than $\Delta_c^{IM}(C)$ unless the profit-sharing method heavily penalizes a high input bid.

Notably, it can be demonstrated that *Input-Max* is an attractive bidding strategy independent of the profit-sharing method used. For that, consider the special case where a positive collaboration gain can only be achieved with the participation of carrier c, i.e.

[14] In the special case that she is allocated her input bundle in the true optimal allocation, increasing her input bid will have no effect. Hence, she should do nothing.
[15] Assuming no ties, i.e. $Z(C) - (Z(S) + e_c) > 0$

$Z(S) = \sum_{i \in S} e_i$. Carrier c's optimal increment Δ_c^{IM} would equal the collaboration gain $g(C)$ as following would hold[16]

$$\Delta_c^{IM}(C) = Z(C) - (Z(S) + e_c)$$

$$\Leftrightarrow \Delta_c^{IM}(C) = (Z(C) - \textstyle\sum_{i \in C} e_i) - (Z(S) + e_c - \textstyle\sum_{i \in C} e_i)$$

$$\Leftrightarrow \Delta_c^{IM}(C) = (Z(C) - \textstyle\sum_{i \in C} e_i) - (\textstyle\sum_{i \in C} e_i - \textstyle\sum_{i \in C} e_i)$$

$$\Leftrightarrow \Delta_c^{IM}(C) = g(C)$$

If carrier c increased e_c by $g(C)$, her marginal profit $\delta_c^{IM}(C)$ would be $g(C) - g_c(C)$ as $g_c^{IM}(C) = 0$ if no collaboration gain is left to share, independent of the profit-sharing method. Since her initial profit was $g_c(C)$, her new profit after considering her marginal profit $\delta_c^{IM}(C)$ would be $g_c(C) + g(C) - g_c(C) = g(C)$. In other words, the carrier would be able to claim all the collaboration gain for herself. Clearly, this is just a special case. But it illustrates that using *Input-Max* can be a very successful bidding strategy independent of the profit-sharing method used.

Another interesting observation is that $\Delta_c^{IM}(C)$ resembles carrier c's marginal contribution to the collaboration gain of the grand coalition C. Hence, $\Delta_c^{IM}(C)$ equals[17] her critical contribution $\psi_c(C)$, as defined by (6.5.1)[18]. Therefore, a carrier who does not know the bids of the other carriers and wants to replicate *Input-Max* should try to estimate her critical contribution $\psi_c(C)$ to the collaboration.

Bidding Strategy 1: Input-Max

In addition, carrier c could try to raise her payment $p_c^{EPM}(C)$ by decreasing her winning bid $w_c(C)$. Essentially, decreasing $w_c(C)$ has the same effect on $p_c^{EPM}(C)$ as increasing e_c. However, if carrier c decreases $w_c(C)$, she should also decrease all her other bids, besides e_c, by the same decrement to avoid that WDP would allocate a different bundle to her. Based on this insight, the bidding strategy *Win-Low* is introduced.

[16] For $\epsilon = 0$
[17] For $\epsilon = 0$
[18] For the mathematical derivation, please be referred to the Appendices

Win-Low. If carrier c is not allocated her input bundle in the true optimal allocation, she should decrease all her bids besides her input bid e_c, i.e. all her bids $\boldsymbol{b}_c{}' = \boldsymbol{b}_c \backslash \{e_c\}$, as much as possible but not so much that she would win her input bid. In other words, carrier c should decrease all her bids $\boldsymbol{b}_c{}'$ up to the threshold where WDP would determine to allocate her input bundle back to her. This is essentially equivalent to the scenario described in *Input-Max*. As a result, carrier c's optimal decrement ∇_c^{WL} for her bids $\boldsymbol{b}_c{}'$ should be calculated like her optimal increment $\Delta_c^{IM}(C)$ for e_c, as defined by (7.1.2),

$$\nabla_c^{WL}(C) = \; Z(C) - (Z(S) + e_c) - \epsilon \tag{7.1.4}$$

Where ϵ is a very small number and S=$C\backslash\{c\}$

Suppose that carrier c's share of the collaboration gain after decreasing all her bids $\boldsymbol{b}_c{}'$ by $\nabla_c^{WL}(C)$ is $g_c^{WL}(C)$, then her resulting marginal profit $\delta_c^{WL}(C)$ can be calculated as follows

$$\delta_c^{WL}(C) = \nabla_c^{WL}(C) - \; [g_c(C) - g_c^{WL}(C)] \tag{7.1.5}$$

Since $\nabla_c^{WL}(C) = \Delta_c^{IM}(C)$, the only difference between $\delta_c^{WL}(C)$ and $\delta_c^{IM}(C)$, as defined by (7.1.3), is that $\delta_c^{WL}(C)$ considers $g_c^{WL}(C)$ while $\delta_c^{IM}(C)$ considers $g_c^{IM}(C)$. If the collaboration gain is shared according to EPM, $\delta_c^{WL}(C) = \delta_c^{IM}(C)$ as $g_c^{WL}(C) = \frac{g(C)-\nabla_c^{WL}(C)}{|C|} = \frac{g(C)-\Delta_c^{IM}(C)}{|C|} = g_c^{IM}(C)$. In other words, if the collaboration gain is shared according to EPM, *Input-Max* and *Win-Low* will lead to the same marginal profit. Hence, both strategies are essentially equivalent, and the carrier may choose one of the strategies arbitrarily. Also, for many other profit-sharing methods this may be the case. However, in general, $g_c^{WL}(C)$ could be different from $g_c^{IM}(C)$.

Bidding Strategy 2: Win-Low

In conclusion, the recommendation for the conspiring carrier is to use *Input-Max* or *Win-Low* to manipulate her bids.

Analysis for the Strategic Carrier

If carrier c is a strategic carrier, she should try to replicate the bidding strategies of the conspiring carrier as good as possible.

Replicating *Input-Max*, she should increase her input bid. However, she cannot calculate the optimal increment $\Delta_c^{IM}(C)$ according to *Input-Max*. Thus, the question is by how much she should increase her input bid. Since the transport collaboration will likely exchange requests on a regular basis, she could try to increase her input bid by different margins, and evaluate which margins led to the most profit on average. Furthermore, she could try to apply sophisticated statistical analyses to predict to what extend she could increase her input bid without winning it. As explained previously, the optimal increment $\Delta_c^{IM}(C)$ for *Input-Max*, as defined by (7.1.2), resembles the carrier's critical contribution $\psi_c(C)$, as defined by (6.5.1). Hence, she should, ideally, determine the increment for her input bid dependent on her estimated critical contribution to the collaboration gain.

Replicating *Win-Low*, she should decrease all her bids besides her input bid. Her optimal decrement $\nabla_c^{WL}(C)$ according to *Win-Low* is the same as her optimal increment $\Delta_c^{IM}(C)$ according to *Input-Max*. Therefore, her approach for finding an appropriate decrement for the bids besides her input bid should resemble her approach for finding an appropriate increment for her input bid. Importantly, she should use the same absolute decrement and not use relative margins. In other words, she should not decrease her bids by x%.

7.2 Analysis for MEPM

Next, the modified egalitarian profit-sharing method is analyzed. The carrier's share of the collaboration gain is $g_c^{MEPM}(C)$, as defined by (6.2.1). The according NIC payment $p_c^{MEPM}(C)$ is calculated as follows

$$p_c^{MEPM}(C) = e_c + \frac{g(C)}{|C'|} - w_c(C) \qquad \text{if } c \in C' \tag{7.2.1}$$

$$p_c^{MEPM}(C) = e_c - w_c(C) \qquad \text{if } c \notin C'$$

Where $C' \subseteq C$ is the set of contributing carriers[19]

Analysis for the Conspiring Carrier

Since MEPM is very similar to EPM, the previous analysis of EPM is still mainly applicable. In particular, the conspiring carrier may use the strategies *Input-Max* and *Win-*

[19] i.e. carriers who are not allocated their own input bundle in the optimal allocation

Low to increase her profit. The difference to EPM is that the carrier's share of the collaboration gain $g_c^{MEPM}(C)$ is dependent on the set of contributing carriers C'.

If carrier c is not part of the contributing carriers, i.e. c $\notin C'$, in the true optimal allocation, she won't receive a share of the collaboration gain, i.e. $g_c^{MEPM}(C) = 0$. Hence, she won't make any profit if she submits her truthful bids. To increase her profit, she may consider manipulating her bids so that WDP determines an alternative allocation where she is part of the contributing carriers and, as a result, gets a share of the collaboration gain. In particular, she may consider decreasing her input bid e_c. However, decreasing e_c is expensive because she is paid e_c. Hence, she should, if at all, decrease e_c by as little as necessary, i.e. up to the threshold where she would win a bid different from input bid. Based on this insight, the strategy *Input-Enter* is introduced.

Input-Enter. If carrier c is allocated her input bundle in the true optimal allocation, she should decrease her input bid e_c so that she would win a different bid, but she should not decrease e_c by more than necessary. In other words, carrier c should decrease e_c up to the threshold where she would be allocated a bundle other than her input bundle. To calculate that threshold, she needs to calculate the value of the optimal allocation subject to the constraint that she is not allocated her input bundle. For this, WDP is modified by adding a constraint that enforces that her input bundle o is not allocated back to her. Suppose that $x^*{}_{co} = 1$ if carrier c is allocated her input bundle o and $x^*{}_{co} = 0$ otherwise, then following constraint is added to WDP:

$$x_{co} = 0 \tag{4}$$

Additional Constraint for WDP^{IE}

The modified WDP is referred to as WDP^{IE}, and the optimal value of WDP^{IE} is referred to as $\text{Z}^{\text{IE}}(C)$. By definition, $\text{Z}^{\text{IE}}(C)$ is the value of the optimal allocation subject to the constraint that carrier c does not get back her input bundle. Notably, if she decreases her input bid e_c by more than $\nabla = Z(C) - \text{Z}^{\text{IE}}(C)$, she won't be allocated her input bundle anymore as $Z(C) - \Delta_c < \text{Z}^{\text{IE}}(C)$. Following this insight, her optimal decrement $\nabla_c^{IE}(C)$ for e_c is calculated as follows

$$\nabla_c^{IE}(C) = \; Z(C) - \text{Z}^{\text{IE}}(C) + \epsilon \tag{7.2.2}$$

Where ϵ is a very small number

Suppose that carrier c's share of the collaboration gain after decreasing e_c by $\nabla_c^{IE}(C)$ is $g_c^{IE}(C)$, then her resulting marginal profit $\delta_c^{IE}(C)$ can be calculated as follows

$$\delta_c^{IE}(C) = [g_c^{IE}(C) - g_c(C)] - \nabla_c^{IE}(C) \tag{7.2.3}$$

If the collaboration gain is shared according to MEPM, $g_c(C) = 0$ because it is assumed that carrier c wins her input bundle in true optimal allocation and, as result, she won't be part of the contributing carriers C'. Hence, for MEPM, $[g_c^{IE}(C) - \mathrm{g(C)}] = \frac{g(C)+\epsilon}{|\mathrm{C^{IE}}|}$ where $\mathrm{C^{IE}}$ is the set of the contributing carriers in the optimal allocation of $\mathrm{WDP^{IE}}$. As $\frac{g(C)+\epsilon}{|\mathrm{C^{IE}}|} \geq \nabla_c^{IE}(C)$ cannot be guaranteed, carrier c should only decrease her input bid e_c by $\nabla_c^{IE}(C)$ if she checked that $\delta_c^{IE}(C) > 0$.

Bidding Strategy 3: Input-Enter

In conclusion, the recommendation for the conspiring carrier is to use *Input-Max*, *Win-Low* or *Input-Enter* to manipulate her bids.

Analysis for the Strategic Carrier

As the conspiring carrier uses *Input-Max* and *Win-Low*, the strategic carrier should either increase her input bid or decrease all the other bids. In Section 7.1, it is described how she may choose her appropriate increment for her input bid or her appropriate decrement for all the other bids. However, compared to EPM, she should manipulate her bids more conservatively because if she manipulates her bids too much, for example, if she increases her input bid so much that she changes the true optimal allocation by winning her input bundle, she will be excluded from getting a share of the collaboration gain.

If carrier c predicts that she won't be part of the contributing carriers in the true optimal allocation, she could try to replicate *Input-Enter* by decreasing her input bid. However, she needs to be quite sure that she won't be part of the contributing carriers because otherwise that strategy will just lead to a loss of her guaranteed payment. In general, decreasing her input bid cannot be recommended.

7.3 Analysis for PSPM

Next, the purchase and sale weighted profit-sharing method is analyzed. The carrier's share of the collaboration gain is $g_c^{PSPM}(C)$, as defined by (6.3.1). The according NIC payment $p_c^{PSPM}(C)$ is calculated as follows,

$$\begin{aligned} p_c^{PSPM}(C) &= \ e_c + \ \varphi_c^{PSPM}(C)g(C) - w_c(C) \\ &= \ e_c + \frac{g(C)}{2}\left(\frac{|e_c|}{\sum_{i\in C}|e_i|} + \frac{|w_c(C)|}{\sum_{i\in C}|w_i(C)|}\right) - w_c(C) \end{aligned} \tag{7.3.1}$$

Analysis for the Conspiring Carrier

The conspiring carrier could raise her payment $p_c^{PSPM}(C)$ by increasing her input bid e_c, decreasing her winning bid $w_c(C)$, or increasing her share of the collaboration gain $g_c^{PSPM}(C)$.

If carrier c does not win her input bid in the true optimal allocation, increasing her input bid e_c by Δ, will increase her payment by $\Delta + \frac{g(C)}{2}\left(\frac{|e_c+\Delta|}{\sum_{i\in C\setminus\{c\}}|e_i|+|e_c+\Delta|} - \frac{|e_c|}{\sum_{i\in C}|e_i|}\right)$. In other words, increasing e_c by Δ, will increase her guaranteed payment and, usually[20], also increase her share of the collaboration gain $g_c^{PSPM}(C)$. Like for *Input-Max*, she should increase her input bid e_c as much as possible but she should avoid winning it. Notably, she can easily prevent winning her input bid e_c if she increases her winning bid $w_c(C)$ by the same absolute increment Δ as e_c. If she increases $w_c(C)$ by Δ, her payment will decrease by $\Delta - \frac{g(C)}{2}\left(\frac{|w_c+\Delta|}{\sum_{i\in C\setminus\{c\}}|w_i|+|w_c+\Delta|} - \frac{|w_c|}{\sum_{i\in C}|w_i|}\right)$. In other words, increasing $w_c(C)$ by Δ, will increase the price she needs to pay for her allocated bundle but, usually[21], also increase her share of the collaboration gain $g_c^{PSPM}(C)$. Hence, carrier c's marginal payment of increasing e_c and $w_c(C)$ by the same increment Δ is

$$\Delta + \frac{g(C)}{2}\left(\frac{|e_c+\Delta|}{\sum_{i\in C\setminus\{c\}}|e_i|+|e_c+\Delta|} - \frac{|e_c|}{\sum_{i\in C}|e_i|}\right) - \Delta + \frac{g(C)}{2}\left(\frac{|w_c+\Delta|}{\sum_{i\in C\setminus\{c\}}|w_i|+|w_c+\Delta|} - \frac{|w_c|}{\sum_{i\in C}|w_i|}\right)$$

$$\Leftrightarrow \ \frac{g(C)}{2}\left[\left(\frac{|e_c+\Delta|}{\sum_{i\in C\setminus\{c\}}|e_i|+|e_c+\Delta|} - \frac{|e_c|}{\sum_{i\in C}|e_i|}\right) + \left(\frac{|w_c+\Delta|}{\sum_{i\in C\setminus\{c\}}|w_i|+|w_c+\Delta|} - \frac{|w_c|}{\sum_{i\in C}|w_i|}\right)\right]$$

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[20] If e_c is negative, this might not be the case

[21] If $w_c(C)$ is negative, this might not be the case

Notably, her marginal payment will, usually[22], be positive. This is the case because, simply put, the direct effects of increasing her input and winning bid by the same increment will cancel out, while her purchase and sale weight $\varphi_c^{PSPM}(C)$, which is used to determine her share of the collaboration gain $g_c^{PSPM}(C)$, will increase. Hence, it can be concluded that increasing her input and winning bid as much as possible by the same absolute increment seems to be a promising strategy as it increases her payment without changing the true optimal allocation. Based on this insight, the bidding strategy *Bid-High* is introduced.

Bid-High. Carrier c should increase all her bids $\boldsymbol{b}_c$, including her input bid e_c and winning bid w_c(C), as much as possible by using the same absolute increment. Hence, carriers c's increment $\Delta_c^{BH}(C)$ for all her bids $\boldsymbol{b}_c$ is

$$\Delta_c^{BH}(C) \approx \infty \tag{7.3.2}$$

Suppose that carrier c's share of the collaboration gain after increasing all her bids $\boldsymbol{b}_c$ by $\Delta_c^{BH}(C)$ is $g_c^{BH}(C)$, then her resulting marginal profit $\delta_c^{BH}(C)$ can be calculated as follows

$$\delta_c^{BH}(C) = g_c^{BH}(C) - g_c(C) \tag{7.3.3}$$

Carrier c's resulting marginal profit $\delta_c^{BH}(C)$ is not directly dependent on her input bid e_c or her winning bid $w_c(C)$. Instead, $\delta_c^{BH}(C)$ reflects the change of her share of the collaboration gain. Notably, the collaboration gain $g(C)$ itself won't change because WDP won't determine a different allocation if all bids increase by the same absolute increment. Hence, carrier c's share of the collaboration gain will only change, i.e. $g_c^{BH}(C) \neq g_c(C)$, if increasing her bids $\boldsymbol{b}_c$ changes how much of $g(C)$ is allocated to her. If the collaboration gain is shared according to PSPM, increasing all her bids $\boldsymbol{b}_c$ by $\Delta_c^{BH}(C)$ will increase her purchase and sale weight to 1, i.e. $\varphi_c^{PSPM}(C) \to 1$, because her input and winning bid will look infinitely more valuable than the input and winning bids of the other carriers. Hence, she would be able to claim all the collaboration $g(C)$ [23]. In general, if the profit-sharing method shares the collaboration gain according to weights

[22] If her input bid e_c and/or her winning bid $w_c(C)$ are negative, this might not be the case

[23] For the mathematical derivation, please be referred to the Appendices

that depend on the magnitude of the carriers' bids, *Bid-High* will be a very successful strategy.

Bidding Strategy 4: Bid-High

In conclusion, the recommendation for the conspiring carrier is to use *Bid-High*.

Analysis for Strategic Carrier

Usually, the strategic carrier cannot perfectly copy the strategies of the conspiring carrier because the strategic carrier does not know the bids of the other carriers. However, in this case, the strategic carrier does not need to know the bids of the other carriers. According to *Bid-High* she should just bid her true valuations increased by the same, infinitely high absolute increment. In theory, if the other carriers bid truthfully, she will be able to claim all the collaboration gain by following this approach. In practice, the carrier may bid more conservative so that her strategy won't be detected. All in all, the profit-sharing method PSPM is very vulnerable to *Bid-High*.

7.4 Analysis for SVPM

Next, the Shapley value profit-sharing method is analyzed. The carrier's share of the collaboration gain is $g_c^{SVPM}(C)$, as defined by (6.4.1). The according NIC payment $p_c^{SVPM}(C)$ is calculated as follows

$$p_c^{SVPM}(C) = e_c + \sum_{S \subseteq C \setminus \{c\}} \frac{|S|!\,(|C|-|S|-1)!}{|C|!}\,[g(S \cup \{c\}) - g(S)] - w_c(C) \qquad (7.4.1)$$

Analysis for the Conspiring Carrier

The conspiring carrier could raise her payment $p_c^{SVPM}(C)$ by increasing her input bid e_c, decreasing her winning bid $w_c(C)$, or increasing her share of the collaboration gain $g_c^{SVPM}(C)$.

As usual, increasing her input bid e_c is an attractive strategy. Hence, carrier c could try to use *Input-Max* and increase her input bid e_c by the increment $\Delta_c^{IM}(C)$, as defined by (7.1.2). Alternatively, she could also try to use the strategy *Win-Low*. Both strategies should achieve similar results.

In addition, carrier c could try to increase her share of the collaboration gain $g_c^{SVPM}(C)$. Recall that $g_c^{SVPM}(C)$ reflects the weighted average of her marginal contributions to the collaboration gains of all coalitions where she could be part of, i.e. all coalitions $S_c = S \subseteq C: c \in S$. Hence, she could try to manipulate her bids so that her reported marginal contributions to the collaboration gains of some coalitions in S_c increase. The easiest way to increase $g_c^{SVPM}(C)$ would be to decrease her input bid e_c or increase her winning bid $w_c(C)$ as this would increase her reported marginal contribution to the collaboration gain of the grand coalition C. The problem with that strategy is that it is expensive to decrease e_c or increase $w_c(C)$ as both moves would, ceteris paribus, decrease her payment.

Interestingly, her allocated bundle in the optimal allocation of the grand coalition C is not necessarily her allocated bundle in the optimal allocation of a sub-coalition in S_c. Hence, she may increase her reported marginal contribution to the collaboration gain of a sub-coalition by increasing a bid that is not her winning bid $w_c(C)$ and not her input bid e_c. Since she only needs to pay her winning bid $w_c(C)$, she could increase all her other bids for free, provided that the true optimal allocation does not change. Hence, carrier c could try to increase all her bids besides $w_c(C)$ and e_c, also referred to as her alternative bids, as much as possible to increase $g_c^{SVPM}(C)$. However, as usual, she should avoid increasing her alternative bids by so much that WDP would fail to determine the true optimal allocation. Hence, it can be concluded that carrier c's strategy should be to increase each bid, which is not her input bid e_c and not her winning bid $w_c(C)$, up to the threshold where she would win it. Based on this insight, the strategy *Alt-Max* is introduced.

Alt-Max. Carrier c should increase each of her bids besides her winning bid $w_c(C)$ and her input bid e_c, i.e. each of her alternative bids $\boldsymbol{b}_c^{alt} = \boldsymbol{b}_c \setminus \{e_c, w_c(C)\}$, as much as possible but not so much that she would win an alternative bid. In other words, carrier c should increase each alternative bid in $\boldsymbol{b}_c^{alt}$ up to the threshold where WDP would allocate the alternative bid's associated bundle to her. Suppose an alternative bid in $\boldsymbol{b}_c^{alt}$ with bundle k. To calculate the threshold where WDP would allocate the alternative bid's associated bundle k to her, carrier c needs to know the value of the optimal allocation subject to the constraint that she is allocated bundle k. For this, WDP is modified by adding a constraint that enforces that she is allocated bundle k. Suppose that $x^*_{ck} = 1$ if carrier c wins bundle k and $x^*_{ck} = 0$ otherwise. Then following constraint is added to WDP

$$x_{ck} = 1 \tag{5}$$

Additional Constraint for $\mathrm{WDP}^{\mathrm{k}}$

The modified WDP is referred to as WDP^k, and the optimal value of WDP^k is referred to as $Z^k(C)$. By definition, $\mathrm{Z}^{\mathrm{k}}(C)$ is the value of the optimal allocation subject to the constraint that carrier c wins bundle k. Hence, carrier c can predict that if she increases her bid for bundle k by less than $\Delta = Z(C) - Z^k(C)$, she won't win her bid on bundle k, as $Z(C) > Z^k(C) + \Delta$. Hence, for each alternative bid with some associated bundle k, her optimal increment $\Delta_c^{AM}(C,k)$ is calculated as follows

$$\Delta_c^{AM}(C,k) = Z(C) - Z^k(C) - \epsilon \tag{7.4.2}$$

Where ϵ is a very small number

Suppose that carrier c's share of the collaboration gain after increasing all her alternative bids $\boldsymbol{b}_c^{alt}$ by their optimal increments $\Delta_c^{AM}(C,k)$ is $g_c^{AM}(C)$, then her resulting marginal profit $\delta_c^{AM}(C)$ can be calculated as follows

$$\delta_c^{AM}(C) = g_c^{AM}(C) - g_c(C) \tag{7.4.3}$$

If the collaboration gain is shared according to SVPM, $g_c^{AM}(C) \geq g_c(C)$ because by increasing her alternative bids $\boldsymbol{b}_c^{alt}$, she can only increase her reported marginal contributions to the collaboration gain, which are used to calculate her share of the collaboration gain.

Notably, *Alt-Max* takes a lot of computational effort because it is necessary to solve $\mathrm{WDP}^{\mathrm{k}}$ for each of the alternative bids $\boldsymbol{b}_c^{alt}$.

Bidding Strategy 5: Alt-Max

In conclusion, the recommendation for the conspiring carrier is to use *Input-Max*, *Win-Low* or *Alt-Max* to manipulate her bids.

Analysis for the Strategic Carrier

The strategic carrier could try replicate *Input-Max* or *Win-Low* by increasing her input bid or by decreasing all her other bids, as explained in Section 7.1.

In addition, she could try to replicate *Alt-Max*. Hence, she could try to increase all her bids, besides her input bid and her winning bid, by as much as possible but not by so much that WDP would fail to determine the true optimal allocation. In contrast to the conspiring carrier, the strategic carrier does not know which bundle would be allocated to her in the true optimal allocation. Also, she does not know by how much she could increase a bid without changing the true optimal allocation. However, she may be able to predict for each of her bids how likely it is that the respective bid would be her winning bid if she bid truthfully. The likelier it is that the respective bid could be her winning bid, the less she should increase that bid. However, this is not an easy strategy to implement and requires statistical analyses.

7.5 Analysis for CWPM

Finally, the critical weight profit-sharing method is analyzed. The carrier's share of the carrier's share of the collaboration gain is $g_c^{CWPM}(C)$, as defined by (6.5.2). The according NIC payment $p_c^{CWPM}(C)$ is calculated as follows

$$\begin{aligned} p_c^{CWPM}(C) &= e_c + \varphi_c^{CWPM}(C) g(C) - w_c(C) \\ &= e_c + \frac{\psi_c(C)}{\sum_{i \in C} \psi_i(C)} g(C) - w_c(C) \\ &= e_c + \frac{g(C) - g(C \backslash \{c\})}{\sum_{i \in C} \psi_i(C)} g(C) - w_c(C) \end{aligned} \tag{7.5.1}$$

Analysis for the Conspiring Carrier

The conspiring carrier could raise her payment $p_c^{CWPM}(C)$ by increasing her input bid e_c, decreasing her winning bid $w_c(C)$, or increasing her share of the collaboration gain $g_c^{CWPM}(C)$. As usual, she could try to use *Input-Max* or *Win-Low* and increase e_c by $\Delta_c^{IM}(C)$, as defined by (7.1.2) , or decrease all her other bids by $\nabla_c^{WL}(C)$, as defined by (7.1.4).

In addition, carrier c could try to increase her share of the collaboration gain $g_c^{CWPM}(C)$ by increasing her critical weight $\varphi_c^{CWPM}(C)$. One way to increase $\varphi_c^{CWPM}(C)$

would be to increase her reported critical contribution $\psi_c(C)$. However, she can only increase $\psi_c(C)$ by decreasing e_c or increasing $w_c(C)$, which would be expensive because both moves would, ceteris paribus, decrease her payment. However, it is also possible to increase her critical weight $\varphi_c^{CWPM}(C)$ by decreasing the reported critical contributions $\psi_i(C)$ of the other carriers $i \in C\backslash\{c\}$. Interestingly, by increasing her alternative bids $\boldsymbol{b}_c^{alt} = \boldsymbol{b}_c\backslash\{e_c, w_c(C)\}$, she may increase the collaboration gains of some sub-coalitions that are used to calculate the critical contributions $\psi_i(C)$ of the other carriers $i \in C\backslash\{c\}$. In other words, by increasing her alternative bids $\boldsymbol{b}_c^{alt}$ it may look like that the other carriers did not contribute so much to the collaboration gain of the grand coalition because their reported marginal contributions to the collaboration gain from a sub-coalition that includes carrier c decreases. Hence, she could try to use *Alt-Max* and increase each of her alternative bids $\boldsymbol{b}_c^{alt}$ by the respective increment $\Delta_c^{AM}(C,k)$, as defined by (7.4.2).

Analysis for the Strategic Carrier

The conspiring carrier uses the same strategies as for SVPM, namely *Input-Max*, *Win-Low* and *Alt-Max*. Hence, the analysis for the strategic carrier should be like the analysis of the strategic carrier for SVPM, which is explained in the Section 7.4.

8 Computational Study

In this chapter, the results of the computational study for the bidding strategies, which are constructed in the previous chapter, are presented.

The test instances are created in a similar way as proposed by Gansterer and Hartl (2016). Gansterer and Hartl (2016) create equidistant depots with a distance of 200 for each carrier, and the requests for a carrier, i.e. the respective pickup and delivery locations, are generated in a radius of 150, 200, or 300 around the carrier's depot. However, they only consider 3 carriers. In this thesis, the tests are conducted for 5 carriers because the profit-sharing methods SVPM and CWPM will be more distinctive if more carriers are considered. Hence, it is impossible to create equidistant depots for the carriers. Instead, the depots are generated on the line of a circle with the radius of 115 such that the depots space out evenly, as illustrated by Figure 4. For the case that 3 depots should be generated, this approach essentially creates the same equidistant depots as in Gansterer and Hartl (2016). However, for the conducted tests, 5 depots are created. Like in

Gansterer and Hartl (2016), the requests for a carrier are randomly generated in a radius of 200 around the carrier's depot. For one test instance, 7 random requests are generated per carrier. In total, 50 test instances are created. The same test instances are used for all conducted tests such that the presented results are comparable.

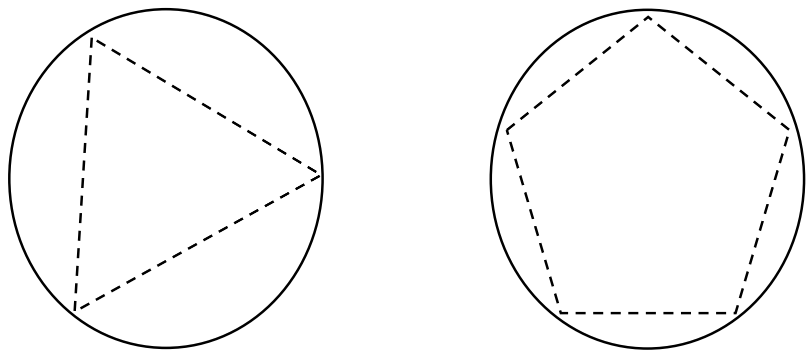


Figure 4: Illustration of the Depot Generation (Left: 3 Depots; Right: 5 Depots)

The implementation of the auction-based mechanism is coded with Python. Table 2 provides a comprehensive overview of the configurations of the coded auction-based mechanism that is used for the tests. For a general overview of the auction-based mechanism, please be referred to Chapter 4.

Number of test instances	50 test instances are generated and used for all conducted tests
Number of carriers	5 carriers participate in the mechanism
Number of initial requests	Initially, each carrier owns 7 requests. Each request has a pickup and a delivery location.
Number of required requests	A carrier is required to own at least 4 requests.
Maximum capacity	A carrier cannot fulfill a route that is 1.3x times longer than her initial route.
Number of offered requests	Each carrier offers up to 2 requests per round. A carrier will offer less than 2 requests, if she otherwise would fall short of her required number of requests.
Profit determination	The profit for each carrier is calculated according to (3.1.1.4) with fixed revenue $r_f = 20$, variable revenue $\lambda = 2$, fixed cost $c_f = 10$, and variable cost $\mu = 1$ (like in Berger and Bierwirth, 2010).

Initial routing solution	The initial routing solution for each carrier is determined by the double-insertion heuristic with 3-opt improvement, as explained in Section 3.3.
Request evaluation	A set of requests is evaluated according to its marginal profit, as defined by (3.1.2.1). For the calculation of the marginal distance, the requests are inserted or deleted from the existing routing solution, as explained in Section 3.3.
Request selection	The request selection strategy "combo_neigh" is used, proposed by Gansterer and Hartl (2016).
Bundle generation	All possible bundles are offered, including the empty bundle.
Bidding	For a selected carrier, various bidding strategies are tested, as explained in Chapter 7. The remaining carriers always bid their true valuations. If the insertion of a bundle's requests would exceed the carrier's max capacity, the carrier will not submit a bid for that bundle.
Winner determination	The winner determination program WDP is implemented as defined in Section 4.4. WDP is solved to optimality by using Google OR-Tools.
Payment calculation	The payment is calculated according to the NIC payment, defined by (5.3.2), combined with the profit-sharing methods that are explained in Chapter 6.
Termination condition	If no collaboration gain can be achieved, the mechanism tries one more time by collecting the second-best set of requests during the request selection phase. If the retry is not successful, the mechanism will terminate.

Table 2: Configurations of the implemented Auction-based Mechanism

Initially, each carrier owns 7 requests. For each round, a carrier offers up to 2 requests to the collaboration, i.e. up to 10 requests are traded per round. Notably, a carrier is required to hold at least 4 requests and the distance of the carrier's route cannot be longer than 1.3x times the distance of her initial route. The capacity constraints are considered because Gansterer and Hartl (2016) show that otherwise often many requests will be allocated to a single a carrier or a small set of carriers.

As described in Chapter 7, we take the perspective of a single carrier c who is either a conspiring carrier or a strategic carrier. For carrier c, the bidding strategies, which are recommended in Chapter 7, are tested and the results are evaluated. Like in Chapter 7, it is assumed that the other carriers bid their true valuations.

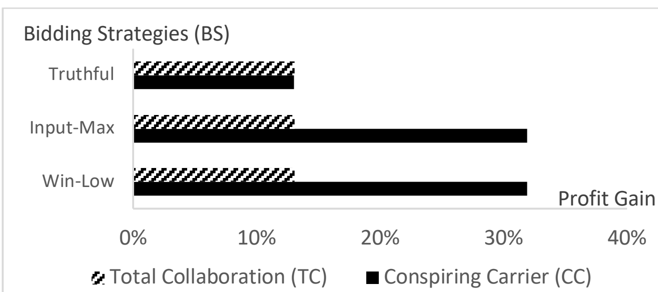
8.1 Results for EPM

First, the results for EPM are presented, i.e. if the carriers' payments are calculated according to (7.1.1). In the truthful scenario, i.e. if all carriers bid truthfully, carrier c's average profit gain from participating in the mechanism is 13.04%, and the average total collaboration gain is 13.06%.

Results for the Conspiring Carrier

If carrier c is a conspiring carrier, she uses the bidding strategies *Input-Max* and *Win-Low*. The results are presented in Figure 5.

By using Input-Max or Win-Low, she increases her profit gain to 31.90%, which is about 2.5x times higher than her profit gain if she bids truthfully. As expected, *Input-Max* and *Win-Low* keep the total collaboration gain unchanged, and both strategies lead to the same results.



BS	CC	TC
Truthful	13.04%	13.06%
Input-Max	31.90%	13.06%
Win-Low	31.90%	13.06%

Figure 5: Results for EPM: profit gains of the conspiring carrier (CC) and profit gains of the collaboration (TC) for different bidding strategies

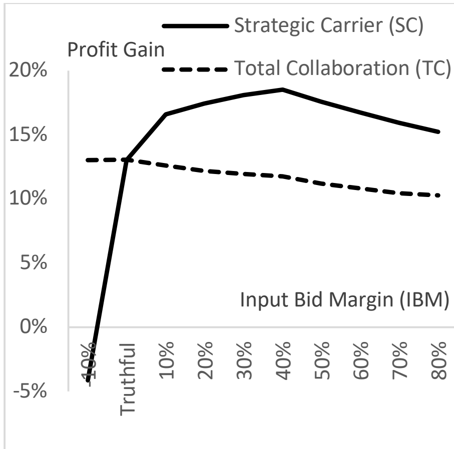
Results for the Strategic Carrier

If carrier c is a strategic carrier, she replicates *Input-Max* by increasing her input bid by different relative margins[24]. The results are presented in Figure 6.

The results show that the carrier can increase her profit gain by increasing her input bid. Her highest recorded profit gain is 18.52%, which she can achieve by increasing her input bid by 40%. Notably, the total collaboration gain decreases if she increases her input

[24] She can also replicate *Win-Low* by decrementing all her bids besides her input bid, the tests show that the results are the same (assuming that she decrements the bids by the same absolute value as she increments her input bid)

bid, i.e. the collaboration becomes less efficient. Hence, if she increases her input bid by more than 40%, her profit gains start to slowly decrease.



IBM	SC	TC
-10%	-4.14%	13.03%
Truthful	13.04%	13.06%
10%	16.6%	12.62%
20%	17.46%	12.19%
30%	18.08%	11.95%
40%	18.52%	11.76%
50%	17.59%	11.18%
60%	16.75%	10.83%
70%	15.92%	10.45%
80%	15.24%	10.28%

Figure 6: Results for EPM: profit gains of the strategic carrier (SC) and the total collaboration (TC) dependent of the input bid margin that the strategic carrier uses to increase her input bid

Conclusion

The results show that the conspiring carrier benefits greatly from using *Input-Max* or *Win-Low*, and it is confirmed that she is indifferent between both strategies. In addition, it can be concluded that the strategic carrier is incentivized to simply overbid her input bid. However, the profit gain from simply overbidding her input bid by a constant relative margin is still significantly lower than her profit gain from *Input-Max*. Hence, in future research, the carrier could try to increase her input bid dependent on her expected critical contribution to the collaboration gain, as explained in Section 7.1.

All in all, the results indicate that EPM is very vulnerable to the strategic manipulation of bids. A carrier is incentivized to simply increase her input bid or, alternatively, decrease all her bids besides her input bid. As a result, the collaboration becomes less efficient. In addition, the results of *Input-Max* and *Win-Low* show that a carrier could more than double her profit gain if she manipulates her bids in a smart way, i.e. if she replicates *Input-Max* or *Win-Low* as good as possible. Hence, EPM should not be used in practice.

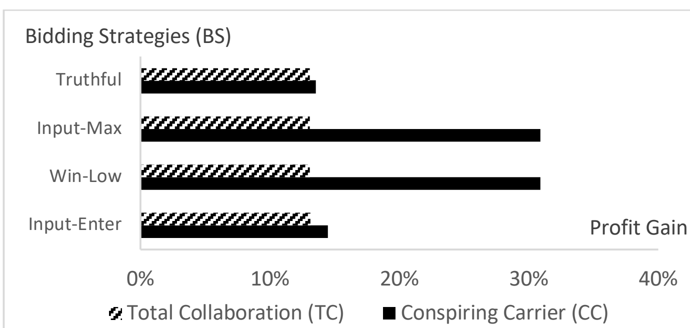
8.2 Results for MEPM

Next, the results for MEPM are presented, i.e. if the carriers' payments are calculated according to (7.2.1). In the truthful scenario, i.e. if all carriers bid truthfully, carrier c's average profit gain from participating in the mechanism is 13.57%, and the average total collaboration gain is 13.06%.

Results for the Conspiring Carrier

If carrier c is a conspiring carrier, she uses the bidding strategies *Input-Max*, *Win-Low*, and *Input-Enter*. The results are presented in Figure 7.

By using *Input-Max* or *Win-Low*, she increases her profit gain to 30.90%, which is about 2.3x times higher than her profit gain if she bids truthfully, and almost as high as for EPM. By using *Input-Enter*, she increases her profit gain to 14.47%, which is only slightly higher than her profit gain if she bids truthfully.



BS	CC	TC
Truthful	13.57%	13.06%
Input-Max	30.90%	13.06%
Win-Low	30.90%	13.06%
Input-Enter	14.47%	13.13%

Figure 7: Results for MEPM: profit gains of the conspiring carrier (CC) and profit gains of the collaboration (TC) for different bidding strategies

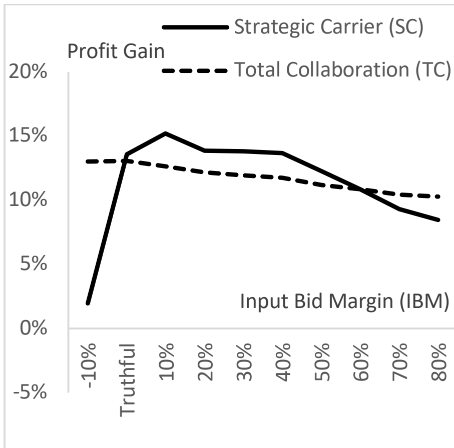
Results for the Strategic Carrier

If carrier c is a strategic carrier, she replicates *Input-Max* by increasing her input bid by different relative margins[25]. The results are presented in Figure 8.

The results show that her highest recorded profit gain from overbidding her input bid by a constant relative margin is 15.20%, which she can achieve by using a relative margin

[25] She can also replicate *Win-Low* by decrementing all her bids besides her input bid, the tests show that the results are the same (assuming that she decrements the bids by the same absolute value as she increments her input bid)

of 10%. Compared to the results for EPM, her highest recorded profit gain from increasing her input bid is significantly lower, and her profit gains decrease faster as the collaboration becomes less efficient. Hence, it is confirmed that, compared to EPM, the strategic carrier should manipulate her bids more conservatively, as explained in Section 7.2.



IBM	SC	TC
-10%	1.96%	13.03%
Truthful	13.57%	13.06%
10%	15.20%	12.62%
20%	13.86%	12.19%
30%	13.8%	11.95%
40%	13.68%	11.76%
50%	12.28%	11.18%
60%	10.84%	10.83%
70%	9.30%	10.45%
80%	8.44%	10.28%

Figure 8: Results for MEPM: profit gains of the strategic carrier (SC) and the total collaboration (TC) dependent of the input bid margin that the strategic carrier uses to increase her input bid

Conclusion

The results show that the conspiring carrier benefits greatly from using *Input-Max* or *Win-Low*. However, if the strategic carrier just simply overbids her input bid by a constant relative margin, she is less successful than for EPM. In other words, the upper limit that a carrier can reach by manipulating her bids is almost as high as for EPM, but she needs to be smarter. Simply overbidding her input bid by a constant margin is not that successful anymore.

All in all, the results indicate that MEPM is more robust against the strategic manipulation of bids than EPM. However, a carrier is still highly incentivized to manipulate her bids in a smart way, i.e. to replicate *Input-Max* or *Win-Low* as good as possible. MEPM may be used in simple settings but using MEPM in practice would be risky because smart carriers may be able to exploit the mechanism significantly.

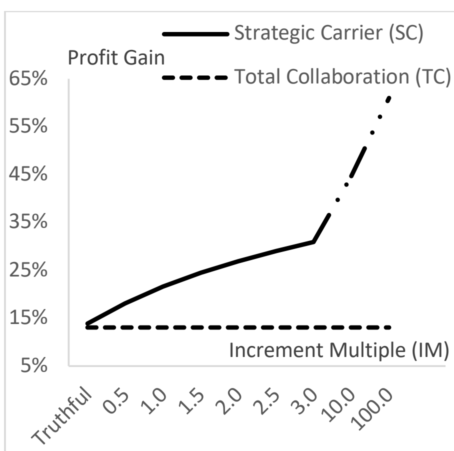
8.3 Results for PSPM

Next, the results for PSPM are presented, i.e. if the carriers' payments are calculated according to (7.3.1). In the truthful scenario, i.e. if all carriers bid truthfully, carrier c's average profit gain from participating in the mechanism is 13.88%, and the average total collaboration gain is 13.06%.

Results for the Conspiring and Strategic Carrier

If carrier c is a conspiring or a strategic carrier, she replicates *Bid-High* by increasing all her bids by an absolute increment. To determine her absolute increment for all bids, she uses her valuation of the input bundle multiplied by a multiple, referred to as the increment multiple[26]. The results are presented in Figure 9.

As expected, her profit gain increases with the increment multiple, i.e. with the magnitude of her absolute increment. If she uses a large increment multiple of 100, her profit gain is over 60%. In addition, the results show, as expected, that the total collaboration gain does not change. In other words, carrier c could claim all the collaboration gain if she used an infinitely high absolute increment.



IM	SC	TC
Truthful	13.88%	13.06%
0.5	18.10%	13.06%
1.0	21.55%	13.06%
1.5	24.45%	13.06%
2.0	26.93%	13.06%
2.5	29.08%	13.06%
3.0	30.97%	13.06%
10.0	44.68%	13.06%
100.0	60.98%	13.06%

Figure 9: Results for PSPM: profit gains of the strategic carrier (SC) and the total collaboration (TC) dependent on the increment multiple that the strategic carrier uses to calculate her absolute increment for all bids

[26] If her valuation of the input bundle is negative, her absolute value of the input bundle is considered

Conclusion

The results confirm that PSPM is very vulnerable to the strategic manipulation of bids. A carrier can increase her profit gain by simply increasing all her bids by the same absolute increment. Hence, PSPM should not be used in practice.

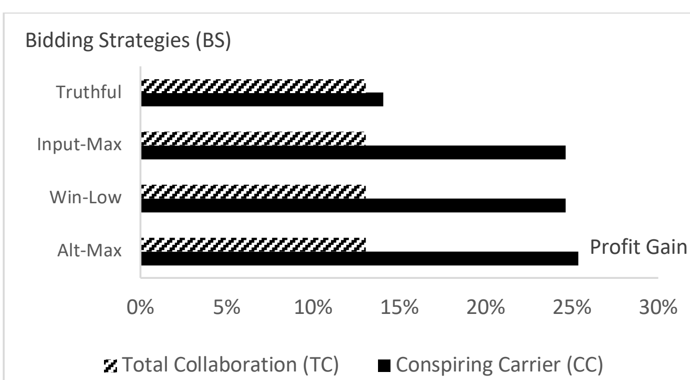
8.4 Results for SVPM

Next, the results for SVPM are presented, i.e. the carriers' payments are calculated according to (7.4.1). In the truthful scenario, i.e. if all carriers bid truthfully, carrier c's average profit gain from participating in the mechanism is 14.06%, and the average total collaboration gain is 13.06%.

Results for the Conspiring Carrier

If carrier c is a conspiring carrier, she uses the bidding strategies *Input-Max*, *Win-Low*, and *Alt-Max*. The results are presented in Figure 10.

By using *Input-Max* or *Win-Low*, she increases her profit gain to 24.62%, which is about 1.8x times higher than her profit gain if she bids truthfully. Both strategies achieve the same results. This is not predicted in Chapter 7, and it indicates that both strategies are essentially equivalent. By using *Alt-Max*, she increases her profit gain to 25.35%, which is slightly higher than for *Input-Max* or *Win-Low*. Notably, her profit gains of using the bidding strategies are high but they are lower than for EPM or MEPM.



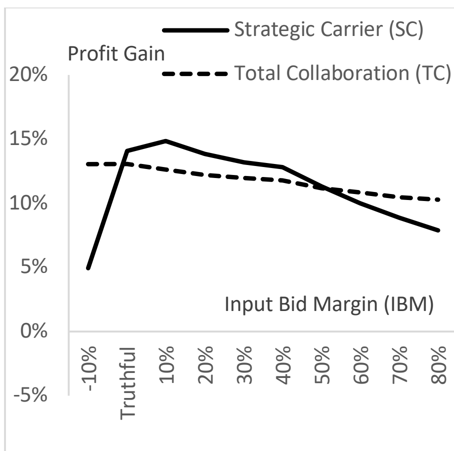
BS	CC	TC
Truthful	14.06%	13.06%
Input-Max	24.62%	13.06%
Win-Low	24.62%	13.06%
Alt-Max	25.35%	13.06%

Figure 10: Results for SVPM: profit gains of the conspiring carrier (CC) and profit gains of the collaboration (TC) for different bidding strategies

Results for the Strategic Carrier

If carrier c is a strategic carrier, she replicates *Input-Max* by increasing her input bid by different relative margins[27]. The results are presented in Figure 11.

The results show that her highest recorded profit gain from overbidding her input bid by a constant relative margin is 14.85%, which she can achieve by using a relative margin of 10%. Hence, she can only slightly increase her profit gain if she increases her input bid by a constant relative margin. In addition, her profit gain decreases faster than for EPM and MEPM if she overbids too much.



IBM	SC	TC
-10%	4.94%	13.03%
Truthful	14.06%	13.06%
10%	14.85%	12.62%
20%	13.86%	12.19%
30%	13.20%	11.95%
40%	12.81%	11.76%
50%	11.31%	11.18%
60%	9.99%	10.83%
70%	8.85%	10.45%
80%	7.89%	10.28%

Figure 11: Results for SVPM: profit gains of the strategic carrier (SC) and the total collaboration (TC) dependent of the input bid margin that the strategic carrier uses to increase her input bid

Conclusion

The results show that the conspiring carrier benefits from using *Input-Max*, *Win-Low,* or *Alt-Max*. However, the profit gain that the conspiring carrier can achieve from using those strategies is smaller than for EPM and MEPM. In addition, simply overbidding her input bid by a constant relative margin is not that successful. In other words, a carrier needs to be smarter. She should try to replicate the strategies *Input-Max* or *Win-Low,* as explained in Section 7.1, or replicate *Alt-Max*, as explained in Section 7.4, as good as possible. The construction of clever strategies that replicate *Input-Max*, *Win-Low* or *Alt-Max* without having full information about the other carriers' bids, would be a good topic of future

[27] She can also replicate *Win-Low* by decrementing all her bids besides her input bid, the tests show that the results are the same (assuming that she decrements the bids by the same absolute value as she increments her input bid). This also indicates that *Win-Low* and *Input-Ma*x are essentially equivalent.

research. In addition, the results indicate that *Input-Max* and *Win-Low* are essentially equivalent and the theoretical argument why this is the case would also be interesting.

All in all, the results indicate that SVPM is more robust against the strategic manipulation of bids than EPM, MEPM, and PSPM. In a strategic environment, SVPM may work reasonably well, but further research would be good.

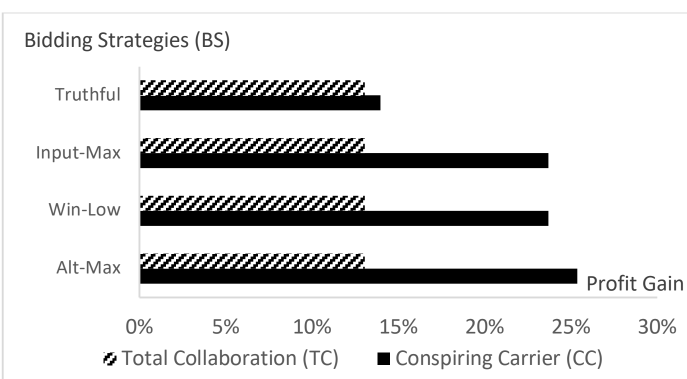
8.5 Results for CWPM

Next, the results for CWPM are presented, i.e. the carriers' payments are calculated according to (7.5.1). In the truthful scenario, i.e. if all carriers bid truthfully, carrier c's average profit gain from participating in the mechanism is 13.96%, and the average total collaboration gain is 13.06%.

Results for the Conspiring Carrier

If carrier c is a conspiring carrier, she uses the bidding strategies *Input-Max*, *Win-Low*, and *Alt-Max*. The results are presented in Figure 12.

By using *Input-Max* or *Win-Low*, she increases her profit gain to 23.69%, which is about 1.7x times higher than her profit gain if she bids truthfully. Both strategies achieve the same results. Like for SVPM, this is also not predicted in Chapter 7, and it indicates that both strategies are essentially equivalent. By using *Alt-Max*, she increases her profit gain to 25.37%, which is slightly higher than for *Input-Max* or *Win-Low*. Notably, the results are very similar to SVPM. Only the profit gains for *Input-Max* and *Win-Low* are slightly lower for CWPM than for SVPM.



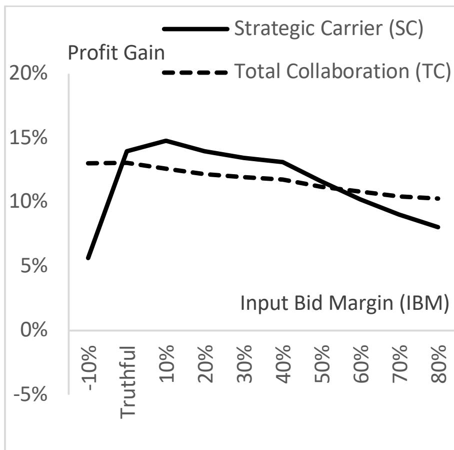
BS	CC	TC
Truthful	13.96%	13.06%
Input-Max	23.69%	13.06%
Win-Low	23.69%	13.06%
Alt-Max	25.37%	13.06%

Figure 12: Results for CWPM: profit gains of the conspiring carrier (CC) and profit gains of the collaboration (TC) for different bidding strategies

Results for the Strategic Carrier

If carrier c is a strategic carrier, she replicates *Input-Max* by increasing her input bid by different relative margins[28]. The results are presented in Figure 13.

The results show that her highest recorded profit gain from overbidding her input bid by a constant relative margin is 14.78%, which she can achieve by using a relative margin of 10%. Again, the results are very similar to the results for SVPM.



IBM	SC	TC
-10%	5.65%	13.03%
Truthful	13.96%	13.06%
10%	14.78%	12.62%
20%	13.95%	12.19%
30%	13.45%	11.95%
40%	13.11%	11.76%
50%	11.60%	11.18%
60%	10.21%	10.83%
70%	9.06%	10.45%
80%	8.07%	10.28%

Figure 13: Results for CWPM: profit gains of the strategic carrier (SC) and the total collaboration (TC) dependent of the input bid margin that the strategic carrier uses to increase her input bid

Conclusion

The results are very similar to the results for SVPM. No evidence can be found that the strategic manipulation of bids is a greater threat for CWPM than for SVPM. The results indicate that *Input-Max* and *Win-Low* may be even less successful for CWPM. Like for SVPM, a strategic carrier needs to be smarter than simply overbidding her input bid by a constant relative margin, if she wants to gain a significant positive marginal profit from manipulating her bids. This is a positive result for CWPM and indicates that CWPM may be a good profit-sharing method to use in practice. Like for SVPM, further research would be good. In particular, the construction of strategies that replicate *Input-Max*, *Win-Low* or *Alt-Max* without having full information about the other carriers' bids, would be a good topic of future research. In addition, it would be good to test CWPM and SVPM again for transport collaborations with more carriers and more requests.

[28] She can also replicate *Win-Low* by decrementing all her bids besides her input bid, the tests show that the results are the same (assuming that she decrements the bids by the same absolute value as she increments her input bid). This also indicates that *Win-Low* and *Input-Ma*x are essentially equivalent.

9 Conclusion

The results of the master's thesis show that if the carriers are paid a share of the collaboration gain according to a profit-sharing method, it is usually not reasonable to assume that the carriers will bid truthfully. The main achievements of this thesis are listed in the following:

- 5 bidding strategies are developed that a conspiring carrier, i.e. a carrier who knows the other carriers' bids in advance, can use to extract a significant amount of the collaboration gain (dependent on the implemented profit-sharing method). If the carrier does not know the other carriers' bids in advance, she should try to replicate those strategies as good as possible.
- It is shown that the bidding strategies *Input-Max* and *Win-Low* can be used independent of the implemented profit-sharing method, and that *Input-Max* and *Win-Low* usually lead to the same results.
- The profit-sharing method CWPM is proposed, which may be more practicable than using SVPM. No evidence can be found that CWPM is less robust against the strategic manipulations of bids than SVPM.
- It is shown that PSPM, as developed by Gansterer et al. (2020), cannot be used in a strategic environment.
- It is shown that, in the conducted tests, MEPM is significantly more robust against the strategic manipulation of bids than EPM.
- It is shown that, in the conducted tests, SVPM and CWPM are more robust against the strategic manipulation of bids than EPM, MEPM, and PSPM.

The most general advice that can be given to a strategic carrier is to either overbid her input bid, or underbid all her bids besides her input bid, by a margin that is as close as possible to her marginal contribution to the collaboration gain of the grand coalition. This strategy should work reasonably well for all profit-sharing methods.

In addition, the thesis concludes that the mechanism should not use the profit-sharing methods EPM or PSPM as both are very vulnerable to the strategic manipulation of bids. For simple settings, it may be sufficient to use MEPM. However, SVPM and CWPM are more robust against the strategic manipulation of bids than MEPM. As SVPM is usually inconceivable to implement in practice (as explained in Section 6.4), CWPM may the best choice of the analyzed profit-sharing methods.

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Appendices

For Section 3.3: Heuristic for the Initial Routing Solution

In the case that the carrier needs to solve the routing problem from scratch, the carrier could use a heuristic that is based on the double insertion heuristic proposed by Renaud et al. (2000) and the 3-opt algorithm proposed by Lin (1965). Gansterer et al. (2020) give evidence that using this heuristic leads to high quality routing solutions in a reasonable amount of time. Hence, for the computational study in Chapter 8, this heuristic is used to determine the initial routing solution for a carrier. To explain the implemented heuristic, three phases, namely the initialization phase, the insertion phase, and the improvement phase, are distinguished.

(1) Initialization Phase

The heuristic starts by determining the transportation request that would lead to the longest initial route from the depot 0. More precisely, the heuristic starts by determining the request with the pickup location $i \in P$ and the delivery location j = $n + i \in D$ with the longest distance $d_{0i} + d_{ij} + d_{j0}$. The determined transportation request is the first request that is inserted in the route. The remaining requests are inserted in the subsequent insertion phase.

(2) Insertion Phase

In the insertion phase, one of the remaining requests is randomly selected and inserted in the route. Since a request consists of a pickup and delivery location, the insertion positions for both locations need to be determined. The insertion positions are selected such that distance of the existing routing solution increases as little as possible. Like in Renaud et al. (2000), it should be considered that the pickup and delivery locations of a request can be inserted consecutively or non-consecutively.

If the request's pickup and delivery locations are inserted consecutively, the delivery location $j = n + i$ is visited directly after the pickup node i. To determine the marginal distance of the route after inserting i and j consecutively between a traversed arc $a = (s, t)$, we need to calculate $d_{si} + d_{ij} + d_{jt} - d_{st}$.

If the request's pickup and delivery locations are inserted non-consecutively, the delivery node $j = n + i$ is not visited directly after its pickup node i. To determine the marginal distance of the route after inserting i and j non-consecutively between the traversed arcs $a = (s, t)$ and $b = (u, v)$, we need to calculate $(d_{si} + d_{it} - d_{st}) + (d_{uj} + d_{jv} - d_{uv})$. Notably, a needs to be visited before b because otherwise the delivery location would be inserted before the pickup location.

After calculating the route's marginal distances for all possible consecutive and non-consecutive insertion positions, the request is inserted according to the insertion positions which lead to the shortest marginal distance of the route.

(3) Improvement Phase

In the improvement phase, the heuristic tries to improve the route that was constructed in the insertion phase. For this, the 3-opt algorithm proposed by Lin (1965) is used. The main idea behind the 3-opt algorithm is to delete 3 arcs of the existing routing solution and reconnect the freed vertices in all possible ways to check whether one of the new routing solutions has a smaller distance, also referred to as the 3-opt move. Figure 14 illustrates how 3 deleted arcs lead to 7 new ways to reconnect the route.

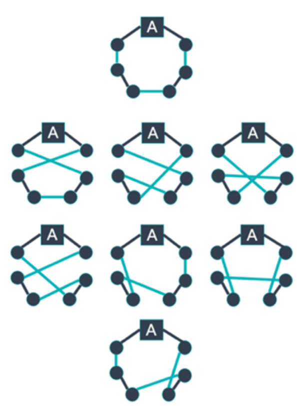

Figure 14: Illustration of the 3-opt moves

Notably, the original 3-opt algorithm assumes that all routing solutions are feasible. However, since a request's pickup location needs to be visited before its delivery location, it cannot be guaranteed that the reconnected route is feasible. Hence, the feasibility of a connected route needs to be checked. To improve the computational efficiency, the feasibility of a new route is only checked after it has been determined that the new route has a smaller distance than the existing route, like suggested by Renaud et al. (2000). If the reconnected route has a smaller distance and is feasible, then the route is updated accordingly, and the 3-opt moves for the updated routing solution are checked. If no 3-opt move can improve the routing solution, then the 3-opt algorithm terminates. Afterwards, the heuristic either returns to the insertion-phase or, if all requests are already included in the route, terminates.

For Section 3.3: Heuristics for Inserting and Deleting Requests

In the case that the carrier already determined a route, the carrier could use the existing route to insert or delete requests. For the computational study in Chapter 8, a carrier uses the following heuristics to insert or delete requests.

Inserting Requests. If the carrier needs to insert requests, the new requests are inserted at their best positions and the route is improved afterwards, like in the insertion and improvement phase of the heuristic for the initial routing solution. However, this time the 2-opt algorithm proposed by Croes (1958) is used to improve the route after the insertion phase. In contrast to the 3-opt algorithm, the 2-opt algorithm only deletes two edges with one possible way to reconnect the freed vertices. Since the 2-opt algorithm considers less alternatives, the running time reduces from $O(n^3)$ to $O(n^2)$ (Renaud et al., 2000). Notably, inserting requests is important to evaluate the marginal profit of a set of new requests, as defined by (3.1.2.1).

Deleting Requests. If the carrier needs to delete requests, the existing route is used to delete the requests. The requests to delete are simply removed from the route, while maintaining the order of the remaining requests. Afterwards, the route is improved by the 2-opt algorithm. Notably, deleting requests is important to evaluate the marginal profit of a set of existing requests, as defined by (3.1.2.1).

For Section 5.2.1: Proof of Individual Rationality for the VCG-Payment

Individual rationality is proofed by contradiction. If carrier c's individual rationality was violated, following would hold

$$\pi_c(C) < 0$$

$$\Leftrightarrow \sum_{k\in T_C} v_{ck}x^*{}_{ck} + p_c^{VCG}(C) - v_{co} < 0$$

$$\Leftrightarrow \sum_{k\in T_C} v_{ck}x^*{}_{ck} + Z(C) - w_c(C) - Z(S) - v_{co} < 0$$

$$\Leftrightarrow \sum_{k\in T_C} v_{ck}x^*{}_{ck} + Z(C) - w_c(C) < Z(S) + v_{co}$$

$$\Leftrightarrow Z(C) < Z(S) + v_{co}$$

The last step can be inferred because carrier c's valuation of her allocated bundle $\sum_{k\in T_C} v_{ck}x^*{}_{ck}$ will equal her winning bid $w_c(C)$ because she is incentivized to bid truthfully[29]. However, the last inequality cannot be true. $Z(C)$ must at least match $Z(S) + v_{co}$. The reason is that the grand coalition C can achieve the same outcome as $Z(S) + v_{co}$ by allocating carrier c's input bundle back to her and allocating the remaining requests according the optimal allocation for S. Thus, assuming that the VCG payment does not ensure individual rationality leads to a contradiction.

[29] In addition, individual rationality is always only guaranteed for truthful participants

For Section 7.1: Derivation that the carrier's optimal increment for her input bid according to Input-Max equals her critical contribution

$\Leftrightarrow \Delta_c^{IM}(C) = \ Z(C) - (Z(S) + e_c)$

$\Leftrightarrow \Delta_c^{IM}(C) = \ Z(C) - \sum_{i \in C} e_i - (Z(S) + e_c - \sum_{i \in C} e_i)$

$\Leftrightarrow \Delta_c^{IM}(C) = \ Z(C) - \sum_{i \in C} e_i - (Z(S) - \sum_{i \in S} e_i)$

$\Leftrightarrow \Delta_c^{IM}(C) = \ g(C) - g(S)$

$\Leftrightarrow \Delta_c^{IM}(C) = \ \psi_c(C)$

For Section 7.3: Derivation that the carrier can claim all the collaboration gain if she is paid according PSPM and increases all her bids by an absolute increment that approaches infinity

$$p_c^{PSPM}(C)' = \lim_{\Delta \to \infty} [(e_c + \Delta) + \frac{g(C)}{2}\left(\frac{|e_c + \Delta|}{\sum_{i \in C \setminus \{c\}} |e_i| + |e_c + \Delta|} + \frac{|w_c + \Delta|}{\sum_{i \in C \setminus \{c\}} |w_i| + |w_c + \Delta|}\right) - (w_c(C) + \Delta)]$$

$$\Leftrightarrow \; p_c^{PSPM}(C)' = \lim_{\Delta \to \infty} [e_c + \frac{g(C)}{2}(\frac{|e_c + \Delta|}{\sum_{i \in C \setminus \{c\}} |e_i| + |e_c + \Delta|} + \frac{|w_c + \Delta|}{\sum_{i \in C \setminus \{c\}} |w_i| + |w_c + \Delta|}) - w_c(C)]$$

$$\Leftrightarrow \; p_c^{PSPM}(C)' = e_c + g(C) - w_c(C)$$

$$\Rightarrow g_c(C) = g(C)$$