Efficiency of Transport Collaboration Mechanisms

Melanie Bloos and Herbert Kopfer

Chair of Logistics, Department of Business and Economics, University of Bremen
Wilhelm-Herbst-Str.5, 28359 Bremen, Germany
Email: {bloos; kopfer}@uni-bremen.de

Abstract: Horizontal cooperation between road haulage contractors is well established in practice. However, over time many cooperations were subject to transformational processes that led their organizations to merge. Here, a concept of collaborative planning, operational transport collaboration, is discussed. This concept achieves higher degrees of organizational autonomy for the participants of cooperation. The idea behind operational transport collaboration is an exchange of transportation requests in order to create competitive advantages in terms of cost and flexibility. For this exchange, mechanisms have to be found that create the best possible allocation of transportation requests to road haulage contractors. Criteria which mechanisms have to comply with in order to create beneficial and desirable solutions for all participants despite the situation of asymmetric information and strategic behavior are derived from microeconomics and game theory. Combinatorial auctions are then discussed as one means of fulfilling these criteria.

Keywords: transport cooperation, exchange mechanism, game theory, microeconomics, combinatorial auction

1. Introduction

Small and medium sized enterprises (SME) face problems of strong competition in the transport sector. Larger enterprises can provide better service and lower prices due to economies of scale and scope. Economies of scale may be achieved by delivering several less-than-truckload (LTL) cargo in one tour and economies of scope by the combination of various tours which might decrease the number of empty returns. One solution for SME discussed in theory and found in practice is cooperation between several enterprises on an operational level.

In the German road transportation sector several horizontal cooperations for LTL cargo are found. The oldest and probably most successful cooperation - in 2007 it came fifth in terms of revenues [11] - is IDS. In terms of revenue, the second and third largest transport cooperations are System Alliance and CargoLine, respectively [21]. What these cooperations have in common is that they started as independent companies cooperating only in parts of their business in the beginning and developing joint organizational structures over time with the individual companies strongly integrated today. Nowadays, they also act like one organizational entity towards the customer. They offer specific products and have a central organizational unit in contact with the customer also assigning transportation requests to the participating road haulage contractors.

The idea discussed in theory (see amongst others [20, 14, 3, 2]) is mainly based on an exchange in operational planning. This means, transportation requests are exchanged between the cooperating partners in order to improve profitability and service performance. Collaborative planning then refers to the planning done jointly for all involved partners in the cooperation. Common to the theoretic approaches is the assumption of independent road haulage contractors entering only a certain share of their transportation requests to the collaborative planning. The remaining share of their requests is planned autonomously by each partner and this planning might go further and include vertical cooperation with subcontractors [13]. Including both fulfillment modes into a road haulage contractor's operational decisions leads to at least three modes of different related cost structures since subcontracting might be subject to more than one type of cost structure as discussed in [15]. The planning situation for the entire system is then unlike the standard assumption for collaborative planning where plans are decided upon centrally [12]. Rather, decentralized planning is found where partners conduct their planning autonomously and only exchange limited information on a certain share of their customers' requests.

The theoretic approach retains a higher degree of autonomy for the cooperating partners than the practical examples mentioned before. The underlying assumption is that SME have the desire to remain economically and organizationally autonomous and may be competitors when entering the cooperation. For collaborative planning this situation implies that not all information will be voluntarily provided and that partners might act strategically and provide incorrect information despite their desire to cooperate.

An exchange mechanism has to be found that helps to reassign the transportation requests in a profitable way despite asymmetric and incomplete information. Further, all payments related to the exchange need to be specified, distributing the costs and financial benefits of the request exchange among the partners. Our contribution is a general analysis of such mechanisms and payment structures and the statement of criteria required of a mechanism in order to be acceptable to the partners. This analysis is based on insights from microeconomics and game theory. The results are not necessarily limited to operational transport collaboration but can also hold for cargo exchange in electronic markets ([9]) or for long-term assignment of transportation routes ([16]).

Section 2 provides an overview of research on operational transport collaboration systems. Then the general properties of operational transport collaboration and the reallocation mechanism as well as criteria for its efficiency are discussed in Section 3. This is followed by a brief discussion of practicability issues for such mechanisms and conclusions in Sections 4 and 5, respectively.

2. Literature Review

Some general considerations for exchanging transportation requests in electronic markets are provided by [9]. The authors discuss the suitability of mechanisms according to the type of transportation orders exchanged. For less than truckload freight with known capacity requirements they find the combinatorial matrix auction most effective. In a matrix auction, the participants submit bids for all bundles of transportation requests (which may include only one request) and a central mechanism determines an efficient allocation of bundles to participants. The bids can be represented by a matrix containing bundles in columns and participants in rows. The allocation is restricted to one bundle per participant and the sum of allocated requests must equal at most the total number and size of requests in the auction ([9] allow the splitting of requests).

One of the first descriptions of cooperation between otherwise competing road haulage contractors is found in [13]. The authors refer to this cooperation as "Groupage System", specified by an extension of transport execution modes (self-fulfillment, subcontracting and fulfillment by partners of the Groupage System). Their definition includes the leveling of transportation capacity across voluntarily cooperating companies who remain legally independent. Various models for the representation of Groupage Systems are discussed ranging from centralized to decentralized planning. The representation also depends on the level of autonomy, such as road haulage contractors as smallest autonomous decision making entity or agents representing each vehicle negotiating the transportation plan.

The model of [20] provides an approach to solving the reallocation problem by a two-step procedure. First, all participants determine profitable requests amongst all requests acquired by the cooperation members. Since it is assumed that requests are unprofitable if served alone requests are bundled with each bundle including all requests of one route. The model assumes that the reallocation is performed by an auctioneer with perfect information on revenue and cost of each request. Thus, the combinatorial auction is a linear integer program minimizing the costs for request execution by identifying the most profitable bundle to carrier allocation. Resulting financial flows are not discussed.

The approach of [14] modifies and extends the model of [20] by considering the related financial flows. The authors suggest a combinatorial auction to solve the reallocation problem where cooperating road haulage contractors bid by stating their minimal execution costs per bundle. The company that has acquired the transportation request originally then keeps the payment from the customer but pays its own minimal fulfillment cost to the coalition (such as a central coordinating unit). The central unit then determines the minimal fulfillment cost of each one-element bundle as specified by the bids and transfers the equivalent sum to the company that has won the request in the auction. The entire remaining revenue at the central unit is then distributed amongst the participants according to activity indices. The mechanism of [14] operates under asymmetric information where participants only reveal request details, the minimal execution costs of the originally acquiring party and bids.

A software system that re-allocates transportation requests among the profit centers of a company is introduced in [10]. The mechanism uses combinatorial auction design for the assignment of geographically clustered requests to profit centers. The authors assume perfect information for this setting and redistribute the commonly achieved revenues according to an exogenously determined activity index.

The problem of including the reallocation of requests in a cooperation into the vehicle routing problem is discussed in [3]. The reallocation is performed by considering all requests for fulfillment in one period and solving a multi-depot vehicle routing problem. The profit sharing assumes the existence of a perfectly informed central instance dividing the revenue between the participants.

3. Reallocation mechanisms

In order to discuss qualities of reallocation mechanisms it is sufficient to study parts of a complex cooperation system in the transportation sector. Assume a set of N road haulage contractors with $i = 1..N$ indicating individual participants in the cooperation. Further, the cooperation includes a set R^+ of requests which has been entered by the cooperating partners into a central pool of requests for reallocation. The preprocessing step, where each road haulage contractor decides between self-fulfillment, forwarding to a subcontractor and assigning requests to the auction for all the acquired requests is omitted here. Thus, $R^+ \subseteq R$ if R is the set of all requests to be fulfilled within the planning horizon. All requests in the central pool have to be reallocated and transfer payments between the road haulage contractors submitting a certain request to the central pool and the acquiring partner actually performing the transportation request have to be defined. The participants may submit and acquire more than one transportation request. As such the acquired requests can be described as bundles of the set R^+ with the set $C = 2^{R^+}$ describing all possible bundles. $b_{ik} \in C$ indicates that bundle k ($k = 1..2^{R^+}$) is assigned to the road haulage contractor i.

The problem of operational transport collaboration can be described as microeconomic coordination problem as [5] shows for scheduling and production problems. Such problems describe the allocation of goods in an economy in a welfare maximizing manner, thus also coordinating individual interests and improving or maintaining the economic status of each participant. In order to do so, a utility function is assumed for each participant, describing the utility gained from each possible allocation of goods.

The quality and efficiency of an allocation mechanism can then be evaluated by the following seven criteria, as discussed in [5], which are explained in detail later on.

- Social welfare
- Pareto efficiency
- Individual rationality
- Stability

- Symmetry
- Computational efficiency
- Distribution and communication efficiency

These criteria are also extended later on for mechanisms operating under asymmetric information. Social welfare is the overall aim for microeconomic mechanisms where goods are distributed in an economy. Welfare can be measured by the sum of the individual utilities the members of the economy have.

For operational transport collaboration we assume perfectly rational participants whose utility for requests can be measured by the marginal profit contribution of these requests. In an economy, participants benefit from the goods themselves and buy them for a certain price. The benefit each transportation request generates is the related transfer payment, t, the acquiring partner receives for performing the transportation request. The marginal profit contribution, u, is then derived from the difference between the transfer payment and the price, p, which the participant pays in order to obtain the request, $u(k) = t(k)-p(k)$. The utilities and thus the participants' payoffs are then quasi-linear [1, 5]. In case of transport collaboration, the price itself is not necessarily transferred but consists of the fulfillment costs for the transportation request. This is a crucial difference to microeconomic markets where the goods are mostly allocated according to the highest valuation and the goods are actually sold. In transport collaboration, the allocation occurs according to the highest possible profit margin because this generates the highest utility values and thus maximizes social welfare. This implies that in contrast to microeconomic markets the mechanism does not determine the price p but the transfer payment related to the request exchange, t.

Participants can express preferences for different bundles. Rational preferences then fulfill the criteria of completeness and transitivity as expressed by equations (1) and (2) [5]. Completeness means that a participant always states the same preference relation for two bundles assigned to her: either she prefers bundle k to bundle m or she prefers m to k. Transitivity helps to derive preference relations since it states that if a participant values a bundle k higher than bundle m and if bundle m is of higher value than x, then bundle k must be of higher value than bundle x to the participant.

$$b_{ik} \succeq b_{im} \vee b_{ik} \preceq b_{im} \qquad \forall (b_{ik}, b_{im}) \in C \times C \qquad (1)$$

$$b_{ik} \succeq b_{im} \wedge b_{im} \succeq b_{ix} \Rightarrow b_{ik} \succeq b_{ix} \qquad (2)$$

The difficulty in determining the valuation of goods lies in finding the combined value for bundles consisting of more than one good or transportation request. In [4] six different types of relations between bundles containing single goods, such as $b_{ik} = \{A\}$ or $b_{im} = \{B\}$, and bundles containing more than one good, $b_{il} = \{A, B\}$ are mentioned. In transport collaboration the value $\widehat{u}(k)$ ($\forall k \in C \setminus \{R^+\}$) of a bundle k with two goods or more depends on the possible integration of the requests into new or existing tours. The transportation requests of a bundle are complementary if they can be jointly integrated into the same tour since they generate higher utility value for the road haulage contractor then. If they can be integrated into different tours the bundle will be evaluated as sum of the values of bundles containing the individual requests since the road haulage contractor is indifferent between receiving them in one or more bundles. The transportation requests of a bundle may have a substitutional relation if not all of the transportation requests can be fulfilled either because of profitability aspects or because of capacity restrictions.

Further, the participants' utilities and preferences only depend on the bundles they receive, that means the utility of a bundle is independent of the allocation of all other bundles to other participants. The utility can be transferred between the participants as financial transfer.

As in an economy a central arbitrator with no self-interest can be assumed in transport collaboration. This arbitrator hosts the reallocation mechanism and intends to establish an efficient allocation of goods – or requests. An allocation $X = (X_0, ...X_n)$ of bundles to participants (with $X_0 = \emptyset$ denoting the bundle assigned to the arbitrator) is called efficient if

$$\sum_{0}^{n} u_i(X_i) = \max_{Y \in A} \sum_{0}^{n} u_i(Y_i) \qquad (3)$$

with A representing all possible allocations [5]. An efficient allocation maximizes social welfare. The reallocation mechanism then determines the efficient allocation of bundles and the pricing for each bundle. Those prices are assumed to be monotone, which means a bundle with more goods in it cannot be sold at a lower price as formally stated by the following equation.

$$t(X) \leq t(Y) \; \forall X, Y \in C \wedge X \subseteq Y \qquad (4)$$

A participant is called satisfied if the assigned bundle maximizes her utility. If all participants are satisfied then according to Walras' law for perfect markets demand and supply are in balance and the market mechanism is efficient. Then the obtained solution is also pareto efficient [5].

The solution to a problem is pareto efficient if there is no other solution improving the situation of one individual without making somebody else worse of. Pareto efficiency implies that none of the road haulage contractors is worse off under collaborative planning than without, which means than when planning with the options of self-fulfillment and subcontracting only. This in turn implies that cooperation has to create a higher overall profit in order to be desirable for the participants and leads to the criterion of individual rationality. Participation is rational, if the participant is no worse off than before. Note, that this assumption excludes any fixed costs the participant might have for entering cooperation - it simply assumes that the participant is indifferent between cooperation and no cooperation if the monetary outcome (profit) is of exactly the same size. Mechanisms are called individually rational if participation is individually rational for each participant.

Further, the mechanism should establish stability, i.e. it has to be incentive compatible and stable against coalitions. Coalitions are further subgroups of the overall participants who try to improve the coalition's situation jointly. A mechanism that is stable against coalitions should produce the same solution for the situation in which every participant acts on her own behalf as for the situation in which she acts on behalf of a joint group strategy. In cooperative game theory such solutions are said to be in the core of the game [14]. Symmetry guarantees that no participant is preferred by the mechanism and that the same input leads to the same output.

When deciding between different mechanisms with similar effects the mechanism with the smallest computational time will always be preferred. A central perfect matching of transportation plans and requests is of high computational complexity. This complexity depends on the number of participants and submitted requests: the number of bundles to be evaluated when N requests have been submitted equals 2^N (assuming that the order in which bundles are assigned is irrelevant). Distribution and communication efficiency refers to the mechanism's ability to deal with incorrect information. Ideally, if one road haulage contractor mistakenly enters a wrong preference or evaluation of a transportation order or if data is missing, the mechanism should not stop but assign all other requests.

A mechanism is acceptable and desirable to all participants if it fulfills the seven criteria mentioned above. However, these criteria assume perfect information and need to be extended for operational transport collaboration with imperfect information and participants striving for personal profit maximization and thus possibly willing to manipulate the mechanism.

The reallocation mechanism needs the specification of information such as available goods and the preferences and utilities of the participants. In operational transport collaboration this information is locally distributed. The utility of each participating road haulage contractor depends on her costs and revenues created by the acquired orders and her utility is based on the efficiency of her individual transportation planning (that is the clustering and tour determination for all requests to be completed in a period). This information is private to the road haulage contractor and as such the transport collaboration is operated under asymmetric information. Then the reallocation needs to include a further step for which the local information is reported to the mechanism in order to find an efficient allocation.

The simplest way to obtain the information required for reallocation would be to ask the cooperating partners for a specification of operational data of all submitted transportation orders and an evaluation of all bundles of transportation orders available in the central pool. Then, each road haulage contractor would reveal the following information on each submitted request: revenue, minimal cost for execution and operational details (locations for pickup and delivery, time windows, cargo specific requirements, size, etc.). For all bundles of requests available for redistribution the road haulage contractor would provide information on her minimal execution cost.

This poses the problem of calculating these minimal execution costs for the road haulage contractor. These costs depend on the updated transportation plans and thus also on other requests acquired from the central pool. If they are specified for all possible bundles of requests in the central pool then a central, optimal solution can be achieved.

The next problem with asymmetric information is that truthful reporting is not necessarily a dominant strategy for all participants. This induces an additional criterion a mechanism has to fulfill: it has to be incentive compatible. Incentive compatible mechanisms provide incentives for participants that make reporting the truth the dominant strategy for each participant. If the mechanism is not incentive compatible then individual participants can manipulate the result, i.e. the efficient allocation.

The model of operational transport collaboration further assumes that all participants do also strive for the highest possible degree of economic and organizational autonomy (cf. Section 1). This aim contradicts a central reallocation mechanism with perfect information and it leads to decentralized planning. However, a central reallocation could extend the decision space of the underlying assignment problem and may lead to a better solution. Participants' willingness to provide necessary and correct information and to transfer the decision right on which bundles they may execute could be reduced if the reallocation mechanism is hosted by one of the participants. These are arguments in favor of an independent operator which can be realized by a web-based reallocation mechanism such as suggested in [10].

Another criterion arising immediately from the nature of operational transportation planning is a frequent repetition of the reallocation mechanism. In some cases, transportation requests for the same or the next day might be incoming hourly and need to be incorporated quickly into the planning. This frequent repetition also leaves the road haulage contractors with more planning flexibility since previous decisions on the order execution might be revised later on. Additionally, updated plans might change the expected cost for performing some of the bundles that had previously been in the central pool. If the mechanism allows resubmitting of requests that do not have to be completed immediately then these bundles can at a later stage be assigned at lower costs. This requires high flexibility and knowledge at the road haulage contractors. A decentralized planning where participants submit only limited information (such as current execution cost for a certain bundle) can then create a more profitable reallocation.

4. Practicability of the mechanism

As discussed in the previous section, the mechanism needs to fulfill a number of criteria regarding its efficiency and including the decentralized planning situation. The two main mechanisms possibly capable of fulfilling these criteria are bilateral negotiations and auctions. Bilateral negotiations can work for small transport collaboration systems where orders are known well in advance and a quick exchange is not necessary. Then, the partners can sell and buy individual transportation requests. However, if the mechanism is to be efficient, then each participant would have to discuss all transportation requests with each other participant and then evaluate each individual request based on the possible bundles she could generate. The complexity of such a mechanism would be very high.

All literature discussed in Section 2 assumes auctions as exchange mechanisms. Since bundling of transportation requests in the central pool is a desirable property combinatorial auctions are suitable. Various forms of combinatorial auctions exist that assign bundles of mostly complementary goods efficiently to bidders [7, 19]. Combinatorial auctions try to establish equilibrium solutions which then fulfill the properties of pareto efficiency, individual rationality and stability. One often discussed form of combinatorial auction is a generalized

Vickrey auction, the so called Vickrey-Clarke-Groves (VCG) mechanism [1]. In this type of auction, all participants submit their evaluations of all bundles available in the auction and an efficient allocation is determined based on these evaluations. The winner of a bundle then pays the opportunity costs of the bundle, i.e. the value difference to the resulting allocation without the winner's participation. This payment is called vickrey payment and in the model of operational transport collaboration as introduced in Section 3 it would be the transfer price, t. This is comparable to the second-price Vickrey auction for single goods and induces truthful bidding as dominant strategy for all participants [1]. This way, the VCG mechanism fulfills the criterion of incentive compatibility.

The matrix auction as suggested by [8] and used by [20, 14] is an extension of the VCG mechanism. Implicit to the VCG mechanism is a first step of determining bundles. In standard auction examples or in many auctions found in practice, such as ebay, bundles are determined by sellers and submitted completely. Operational transport collaboration needs a preprocessing step, where all bundles are determined. In the matrix auction the assumption is that each transport request can be combined with any other request. Then all participating road haulage contractors submit their evaluations for all bundles.

The VCG mechanism in general is related to three problems. First, it depends on the optimal solution of the allocation problem, the so called winner determination problem [19]. Due to the underlying complexity created by the number of possible bundles, the winner determination problem is NP-complete [17]. Suggested solutions of mechanism design include reductions of problem size by limiting the number of bundles to be assigned in advance. Secondly, the VCG mechanism does require all exact bundle evaluations (or utilities in the more general case) for each bidder [1]. Alternatives to exact evaluations are suggested in research on preference elicitation. Preference elicitation strives for an efficient allocation of bundles with less detailed information stated by the participants. For real-world combinatorial auctions preference elicitation has been named "key bottleneck" because of the communication cost of submitting an exponential number of bids and because of the cost bidders occur when calculating their valuations [18]. Further, the aspect of a reluctance to reporting crucial information in informationally decentralized settings can be added. Solutions include automated evaluations of bundles, such as the rank based preference elicitation in [6], or iterative auctions as discussed in [18]. And thirdly, although the VCG mechanism induces truthful bidding it is still manipulable by the auctioner or by bidders and might be subject to false bidding, as for example sellers submitting false bids to push the transfer price [19].

If an auction is used in operational transport collaboration, then these challences in relation to computational efficiency have to be solved. Complete bundle evaluation in transport collaboration requires the solution of an exponential number of transportation planning problems. For matrix auctions the rather technical problem of how to evaluate unwanted bundles arises further. Preference elicitation mechanisms can be important to operational transport collaboration between independent companies since one of the obstacles to the cooperation is certainly trust in relation to the revelation of cost and customer data. Further, auctions including preference elicitation mechanisms are more likely to fulfill the criterion of distribution and communication efficiency.

5. Conclusion

Operational transport collaboration can create competitive advantages for participating companies. In order to be successful a common exchange mechanism between those companies has to be found. General criteria are provided derived from microeconomic theory and intended for the evaluation of the efficiency of a system distributing bundled goods in an economy. The situation of planning by autonomous partners as found in transport collaboration is an extension of the theoretical case of perfect information towards asymmetric information and decentralized planning. Therefore, the criteria have been extended by the requirements of incentive and decentralized planning compatibility.

The major challenge for future research on transport collaboration mechanisms lies in the computational complexity of the underlying problems of evaluating transportation requests and reallocating them between the collaborating partners. Further, the situation of sellers has not been considered here but needs to be addressed. Every participant may take the position of seller and buyer at the same time. It is rational for the seller to attempt to create additional profit by selling transportation requests. However, if this additional profit becomes too large it may contradict an efficient solution. Additionally, sellers might not necessarily provide correct information on transportation requests and thus endanger the calculation of efficient transfer prices. Mechanisms of profit sharing as introduced in [14] deal with an incentive compatible compensation of sellers and should be included into transport collaboration mechanisms.

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