PRICE-SETTING BASED COMBINATORIAL AUCTION APPROACH FOR CARRIERS' COLLABORATION IN LESS THAN TRUCKLOAD TRANSPORTATION

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Abstract: In collaborative logistics, multiple carriers may form an alliance to optimize their transportation operations through sharing transportation requests and vehicle capacities. In this paper, we study a carriers' collaboration problem in less than truckload transportation with pickup and delivery requests. After formulating the problem as a mixed integer programming model, an iterative price-setting based combinatorial auction approach based on Lagrangian relaxation is proposed. Numerical experiments on randomly generated instances demonstrate the effectiveness of the approach.

1 INTRODUCTION

In collaborative logistics, multiple carriers may form an alliance to optimize their transportation operations by sharing vehicle capacities and delivery requests. The objective of the collaboration is to eliminate empty back hauls, to raise vehicle utilization rate, and thus to increase the profit of each carrier involved.

In practice, two types of transportation services are often provided: truckload (TL) transportation and less than truckload (LTL) transportation. Until now, most studies on collaborative logistics were focused on TL transportation (Kwon et al. 2005; Ergun et al. 2007a, 2007b; Lee et al. 2007), few papers studied collaborative logistics problems in LTL transportation (Krajewska and Kopfer, 2006; Houghtalen et al., 2007; Berger and Bierwirth 2010).

Combinatorial auction has been applied to truckload transportation service procurement and carriers' collaboration. However, previous studies adopt a quantity-setting based combinatorial auction approach. In each round, carriers (bidders) submit prices on various bundles of requests. The auctioneer then makes a provisional allocation. The approach requires the pre-selection of preferable bundles by each carrier and the resolution of a NP-hard winner determination problem by the auctioneer in each round. The price setting based auction approach, to be adopted in this paper, can overcome the two difficulties.

In this paper, we study a carrier collaboration problem in less than truckload transportation with pickup and delivery requests (quoted as CCPLTL hereafter), where multiple carriers constitute a transportation alliance for sharing their vehicle capacities and transportation requests. A price-setting based iterative combinatorial auction approach is proposed for reallocating the requests among the carriers. In the approach, the role of the auctioneer is to set and update the price of serving each request, and its objective is to maximize the total profit of the whole alliance. Each bidder (carrier) selects its preferable requests to serve by maximizing its individual profit based on the prices proposed by the auctioneer. The price update is based on Lagrangian relaxation. When the auction process is terminated, if there are still some requests selected by more than one carrier, the conflict is resolved by using a random method. The effectiveness of the approach is demonstrated by numerical experiments on random generated instances.

2 PROBLEM DESCRIPTION

In the carriers' collaboration problem considered,

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multiple carriers operating in a transportation network form a collaborative alliance to share their transportation requests and vehicle capacities, in order to increase their vehicle utilization rates and reduce their empty back hauls. Initially, each carrier has acquired certain requests from shippers (the customers of the carrier), where each request is specified by a pickup location and a time window, a quantity, and a delivery location and a time window. We assume that all requests acquired by the alliance are available to all carriers, this implies that all the requests must be reallocated among all the carriers by using a collaborative transportation planning method. If a request acquired by a carrier is not served by itself, then the carrier has to transfer part of the revenue of the request paid by a shipper to the carrier serving the request. The objective of the collaborative planning is to find an allocation of requests to each carrier as well as optimal vehicle tours for executing the allocated requests subject to the capacity constraint of each vehicle and the time window constraints of each request so that the total profit of the alliance is maximized. After the request reallocation, the profit of the alliance must be fairly allocated among all the carriers so that they are willing to remain in the alliance. For simplicity, in this study we assume that all carriers have vehicles of the same capacity and each carrier uses the same tariffs to calculate its transportation costs.

3 PRICE-SETTING BASED COMBINATORIAL AUCTION FRAMEWORK

Motivated by a combinatorial auction mechanism for truckload transportation service procurement (Kwon et al., 2005; Lee et al., 2007), we propose a combinatorial auction framework with associated models for CCPLTL. In this framework, the reallocation of transportation requests among carriers is realized through a multi-round combinatorial auction. Two types of actors exist in our framework, auctioneer and bidders. The auctioneer is a virtual coordinator who sets and updates the price of serving each request. The objective of the auctioneer is to maximize the total profit of the alliance subject to the constraint that each request is allocated to at most one carrier finally. The bidders, who are the carriers, select their preferable requests to serve by maximizing their individual profits based on the prices proposed by the auctioneer. Contrary to the quantity-setting based combinatorial auction which requires the pre-selection of preferable bundles by each carrier in each round, our proposed auction is a lagrangian relaxation based price-setting auction which does not require the pre-selection. The auction framework we propose consists of the following steps.

(1) Before the auction, each carrier (bidder) submits its requests open to auction to the auctioneer through a common platform. These requests are recorded in a request pool for auction of the auctioneer. Every request has an ask price offered by a shipper (the amount of money paid by the shipper for the service of the request). This price is kept by the carrier who receives the request and will not be known by other carriers.

(2) The auctioneer sets an initial price (referred to as outsourcing price hereafter) for serving each request in the pool, which is equal to or less than the ask price of the request.

(3) The bidders express their selections of requests based on the current outsourcing prices of all requests announced by the auctioneer. All requests in the pool are available to each bidder, and each bidder selects a set of available requests to serve to maximize its own profit. The decision problem of each carrier is referred to as a bidding problem which will be formulated in the next section.

(4) The auctioneer adjusts the outsourcing price of each request. By relaxing the constraints that each request is served by at most one bidder using lagrangian relaxation, the prices are adjusted based on the subgradient which is defined as the violations of the relaxed constraints by the current request selections of all bidders.

(5) Repeating the above steps (3) and (4) until a stopping criterion is satisfied, namely, all requests in the pool are reallocated to at most one carrier or the current best allocation can not be improved in a given number of iterations, or a given number of iterations are achieved.

(6) If there are still some requests selected by more than one bidder after the above mentioned iterative auction process is terminated, a random conflict resolution method is applied to reallocate the requests to the bidders.

(7) After the iterative auction process, each bidder gains a profit by serving some requests (referred to as pre-profit hereafter), which is calculated by solving the relevant bidding problem. The auctioneer holds a residual profit which is the difference between the total profit of the alliance and the pre-profits of all the carriers. This residual profit is

redistributed to all bidders based on a profit sharing mechanism, which ensures that the profit of each carrier gained with the collaboration is no less than its profit gained without collaboration. This mechanism will be discussed in our future work.

The interactions between auctioneer and multiple bidders in each round are illustrated in Figure 1.

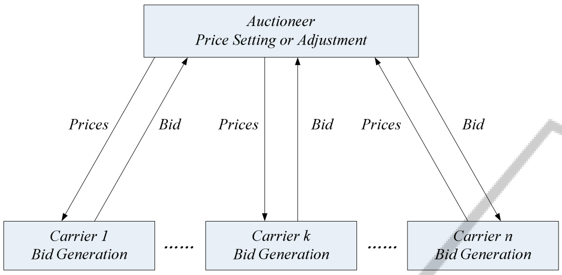

Figure 1: The interactions between auctioneer and multiple bidders in each round.

The advantages of our auction framework are explained as follows: the ask price of each request is reserved by the bidder who owns this request and not known by other carriers; the bidders need not submit bids in forms of bundles of requests but select their preferable requests, this can significantly reduce the computation complexity for considering exponential number of bundles of requests (2^n for n requests). In addition, our framework extends the work of Kwon et al. (2005) and Lee et al. (2007) for truckload transportation service procurement to carrier collaboration in LTL transportation.

4 FORMULATION OF THE COMBINATORIAL AUCTION PROCESS

In this section, we formulate the combinatorial auction process for CCPLTL, which includes a global optimization model for the alliance, the bidding problem for each carrier, and the iterative price adjustment by auctioneer.

4.1 Global Optimization Model

For simplicity, we assume that no more than one transportation request is associated with each node in the transportation network considered.

Indices

$i, j, m = 1, \ldots, N$ node index, where N represents the number of nodes in the transportation network. The nodes include the locations of all shippers, the locations of all customers of the shippers, and the vehicle depots of all carriers.

$k = 1, \ldots, K$ carrier index, where K represents the number of carriers.

$l = 1, \ldots, L$ request index, where L represents the number of requests.

Parameters

P_i the set of requests whose pickup site is node i

D_i the set of requests whose delivery site is node i

d_l quantity delivered on request l

p_l price paid by a shipper to serve request l

C vehicle capacity

W_k the number of vehicles owned by carrier k

o_k the depot of carrier k

c_{ij} shipping cost from node i *to* j for each vehicle where $c_{ij} = c_{ji}$ and the triangle inequality $c_{im} + c_{mj} \geq c_{ij}$, holds for any i, j, m with $m \neq i, m \neq j$

t_{ij} travelling time of a vehicle from node i to node j

a_i the earliest service time at node i

b_i the latest service time at node i

T_{ij} a large number, $T_{ij} = b_j - a_i$

Variables

q_{ij}^k quantity transported through arc (i, j) by carrier k

x_{ij}^k the number of times that arc (i, j) is visited by vehicles of carrier k

y_{lk} 1 if request l is served by carrier k; otherwise 0

t_i^k the time at which a vehicle of carrier k leaves node i

With the notation, the total profit optimization problem of the alliance can be formulated as a mixed integer programming model P as follows:

Model P:

$$Z = Max\left(\sum_{k=1}^{K}\sum_{l=1}^{L} p_l \cdot y_{lk} - \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1, j\neq i}^{N} c_{ij} \cdot x_{ij}^k\right) \tag{1}$$

Subject to:

$$\sum_{j=1, j\neq i}^{N} x_{ij}^k = \sum_{j=1, j\neq i}^{N} x_{ji}^k, i = 1, \ldots, N, i \neq \{o_k\}, k = 1, \ldots, K, \tag{2}$$

$$q_{ij}^k \leq C \cdot x_{ij}^k, i, j = 1, \ldots, N, i \neq j, k = 1, \ldots, K, \tag{3}$$

$$\begin{cases} \sum_{j=1, j\neq i}^{N} q_{ij}^k - \sum_{j=1, j\neq i}^{N} q_{ji}^k = \sum_{l\in P_i} d_l \cdot y_{lk} - \sum_{l\in D_i} d_l \cdot y_{lk}, \\ i = 1, \ldots, N, k = 1, \ldots, K, \end{cases} \tag{4}$$

$$\sum_{j=1, j\neq o_k}^{N} x_{o_k j}^k = \sum_{j=1, j\neq o_k}^{N} x_{j o_k}^k, k = 1, \ldots, K, \tag{5}$$

$$\sum_{j=1, j\neq o_k}^{N} x_{o_k j}^k \leq W_k, k = 1, \ldots, K, \tag{6}$$

$$\sum_{k=1}^{K} y_{lk} \le 1, l = 1,...,L, \tag{7}$$

$$\sum_{j=1, j\ne i}^{N} x_{ij}^k \le 1, i = 1,...,N, i \ne \{o_k\}, k = 1,...,K, \tag{8}$$

$$t_j^k \ge t_i^k + t_{ij}\cdot x_{ij}^k - T_{ij}\cdot\left(1 - x_{ij}^k\right), i, j = 1,...,N, i, j \ne o_k, i \ne j, k = 1,...,K, \tag{9}$$

$$\sum_{j=1, j\ne o_k}^{N} q_{o_k j}^k = \sum_{l\in P_{o_k}} d_l \cdot y_{lk} - \sum_{l\in D_{o_k}} d_l \cdot y_{lk}, k = 1,...,K, \tag{10}$$

$$x_{ij}^k \ge 0, x_{ij}^k \in Z, i, j = 1,...,N, i \ne j, k = 1,...,K, \tag{11}$$

$$y_{lk} \in \{0,1\}, y_{lk} \in Z, l = 1,...,L, k = 1,...,K, \tag{12}$$

$$y_{lk} \in \{0,1\}, y_{lk} \in Z, l = 1,...,L, k = 1,...,K, \tag{13}$$

$$0 \le a_i \le t_i^k \le b_i, i = 1,...,N, i \ne o_k, k = 1,...,K, \tag{14}$$

The objective function (1) represents the total profit of the alliance. Constraints (2) ensure that the number of vehicles leaving from each node is equal to the number of vehicles arriving at this node. Constraints (3) are the vehicle capacity constraints. Constraints (4) are the flow conservation equations, assuring the flow balance at each node. Constraints (5) guarantee that the number of vehicles of carrier k leaves from depot o_k is equal to the number of vehicles arrives at this depot. Constraints (6) imply that no more than W_k vehicles can be used by carrier k. Constraints (7) guarantees that each request is allocated to at most one carrier. Constraints (8) ensure that each pickup/delivery node is visited by each carrier at most once. Constraints (9) denote the relations between departure times t_i^k . Constraints (10) imply that only empty vehicle is returned to the depot of each carrier. Constraints (14) are time window constraints for pickup and delivery operations of the requests. Since at most one request is associated with each node, the constraints are associated with the nodes.

Note that a solution of model P does not completely define vehicle tours for each carrier, but they can be constructed based on the solution by applying a tour generation method proposed in our previous work (Dai and Chen, 2009a, 2009b).

4.2 Iterative Auction based on Lagrangian Relaxation

Based on model P, we propose an iterative price-setting combinatorial auction for the total profit maximization of the alliance. The prices in this auction are the Lagrange multipliers we introduce for relaxing constraints (7) in the model. The relaxed problem can be decomposed into several subproblems, one for each carrier, which determines the preferable requests to bid by the carrier at the current price for serving each request given by the auctioneer. This subproblem is referred to as the bidding problem of the carrier. The price adjustment of the auctioneer in each iteration (round) is based on the subgradient defined as the violations of the relaxed constraints by the current request selections of all carriers. The auction process will be terminated until some condition is satisfied.

4.3 Bidding Problem for each Carrier

To formulate the bidding problem for each carrier, we rewrite objective function (1) as objective function (15),

$$Z = Min - \left(\sum_{k=1}^{K}\sum_{l=1}^{L} p_l \cdot y_{lk} - \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1, j\ne i}^{N} c_{ij}\cdot x_{ij}^k \right) \tag{15}$$

which transforms model P into an equivalent minimization problem. We then relax constraint (7) by introducing the Lagrange multipliers $\lambda = \{\lambda_l \ge 0, l = 1,...,L,\}$, leading to the following relaxed problem SP_{LR}:

$$\begin{aligned} Z_{LR} &= Min \left(\begin{array}{l} -\left(\sum_{k=1}^{K}\sum_{l=1}^{L} p_l \cdot y_{lk} - \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1, j\ne i}^{N} c_{ij}\cdot x_{ij}^k \right) \\ +\sum_{l=1}^{L} \lambda_l \cdot \left(\sum_{k=1}^{K} y_{lk} - 1 \right) \end{array} \right) \\ &= Max \left(\begin{array}{l} \sum_{k=1}^{K}\sum_{l=1}^{L} p_l \cdot y_{lk} - \sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1, j\ne i}^{N} c_{ij}\cdot x_{ij}^k \\ -\sum_{l=1}^{L} \lambda_l \cdot \sum_{k=1}^{K} y_{lk} + \sum_{l=1}^{L} \lambda_l \end{array} \right) \end{aligned} \tag{16}$$

subject to constraints (2) to (6), (8) to (14).

The relaxed problem can be decomposed into k subproblems SP_{LR}^k, one for each carrier k, which is the bidding problem of carrier k.

Subproblem SP_{LR}^k:

$$\begin{aligned} Z_{LR}^k &= Max \left(\sum_{l=1}^{L} p_l \cdot y_{lk} - \sum_{i=1}^{N}\sum_{j=1, j\ne i}^{N} c_{ij}\cdot x_{ij}^k - \sum_{l=1}^{L} \lambda_l \cdot y_{lk} \right) \\ &= Max \left(\sum_{l=1}^{L} (p_l - \lambda_l)\cdot y_{lk} - \sum_{i=1}^{N}\sum_{j=1, j\ne i}^{N} c_{ij}\cdot x_{ij}^k \right) \end{aligned} \tag{17}$$

subject to constraints (2) to (6), (8) to (14) associated with carrier k.

Accordingly, an upper bound for model P can be calculated by (18).

$$\overline{Z_{LR}} = \sum_{k=1}^{K} Z_{LR}^k + \sum_{l=1}^{L} \lambda_l \tag{18}$$

In model SP_{LR}, p_l is the ask price of request l (the price paid by a shipper to serve request l), and Lagrange multipliers λ_l are given by the auctioneer.

The combinatorial auction process considered then consists of the following steps.

Step1, auctioneer sets an outsourcing price for each request, i.e., the value of (p_l -λ_l).

Step2, Each bidder (carrier) determines which requests to serve by solving its bidding problem SP_{LR}^k.

Step3, the auctioneer adjusts the outsourcing prices by updating λ_l based on the violations of the relaxed constraints.

Step4, repeat the above process until no constraint is violated, i.e., each request is allocated to at most one carrier, or a limit number of iterations is achieved. For the latter case, the allocation is infeasible because some requests are allocated to more than one carrier. In this case, the auctioneer randomly allocates each of the requests to one carrier.

4.4 Iterative Price Adjustment by Auctioneer

As we mentioned, the subgradient method (Fisher, 2004) is used to update the Lagrange multipliers. Given an initial value λ^0, the value of λ in the m-th iteration of the auction, denoted by λ^m, is calculated by the equation (19).

$$\lambda_l^{m+1} = Max\left\{\lambda_l^m + t_m \cdot \left(\sum_{k=1}^{K} y_{lk} - 1\right), 0\right\}, l = 1, ..., L, \tag{19}$$

In equation (19), y_{lk} is provided by carrier k after solving its bidding problem SP_{LR}^k at the m-th iteration; t_m is a positive scalar step size, it is set to a fixed amount δ initially. If the objective value of SP_{LR} is not improved in a given number of iterations, δ is halved, i.e., $\delta = \delta/2$.

Three stopping conditions are used in the combinatorial auction iteration process. If one of them is satisfied, the process will be terminated.

(1) No constraint of (7) in model P is violated.

(2) The number of iterations performed exceeds a predefined number.

(3) The current step size δ is smaller than a given small value.

5 NUMERIC EXPERIMENTS

Up to now, there are no benchmark instances for CCPLTL, so all instances used to evaluate the performance of our proposed combinatorial auction approach are generated randomly. These instances are grouped into two sets, which are different in the generation of the coordinates of each node.

All instances involve three carriers ($K = 3$) whose vehicles have the same capacity $C = 10$. The number of transportation requests L is set to $(N\text{-}K)/2$ ($L = 15$). The requests are generated by randomly choosing a pickup node i ($i \neq$ any depot) and a delivery node j ($j \neq i$ and any depot), each node is associated with at most one request; each request is associated with a randomly generated quantity of freight d which is no larger than a predefined number, which is set to 2, 5, 10 for generating 5, 5, 5 instances respectively in each set. Given a request with pickup node i and delivery node j acquired by a carrier from its shipper, the ask price of serving the request is set as $\alpha*(1+\beta)*d*(c_{oi}+c_{ij}+c_{jo})/C$, where o and β denote the depot of the carrier and the profit margin (set to 0.05) of the carrier, respectively, d is the quantity of the request, $(c_{oi}+c_{ij}+c_{jo})$ is the direct shipping cost for the request, α is the vehicle utilization rate of the carrier. The time windows are generated in the following way: the time interval for serving all requests is set to [0, 144] (1440 minutes = 24 hours, time unit is taken as 10 minutes); the earliest service time a_i at pickup node i is randomly chosen from 0 to 60, the latest service time b_i is randomly chosen from (a_i + 6) to 72; the earliest service time a_j at delivery node j is randomly chosen from 72 to 132, and latest service time b_j is randomly chosen from (a_j + 6) to 144. The bidding problem of each carrier is solved by the MIP solver of ILOG Cplex 11.2 for all instances. The time limit for the resolution of each bidding problem is set to one hour. The initial value of each Lagrange multiplier is set to 0; the step size δ is initially set to 50 and its minimum value is to 0.001; δ is halved if the objective value of SP_{LR} is not improved in 10 iterations; the maximum number of iterations for the auction is set to 200.

The number of nodes is set to 33. For each instance in the first set, the coordinates data of the first 33 nodes of benchmark instance R101 of VRPTW (Solomon, 2005) are used, where node 5, 17, 11 are chosen as the depots of the three carriers respectively. Each carrier has 10 vehicles. For each instance in the second set, the coordinates of each node are randomly generated from 66×66 square. After the coordinates of all nodes are generated, the Euclidean distance d_{ij} between any two nodes i and j is calculated. Without loss of generality, we set c_{ij} = t_{ij} = c_{ij}. Every carrier randomly selects a node as its depot which is different from the depot nodes of all other carriers; each carrier owns a number of vehicles randomly chosen from 1 and 10.

All computational results are given in Table 1 and 2, where the row *Quantity* ≤ 2, ≤ 5, ≤ 10 indicates the maximal pickup/delivery quantity generated for each request. The results presented in row *Opt* are obtained by solving the global optimization model *P* of each instance using Cplex 11.2 with a time limit of 2 hours. The row *CAFLB* and *CAFUB* denote the lower bound and the upper bound obtained by our combinatorial auction approach, respectively. The row *Gap* denotes the percentage difference between *CAFLB* and *CAFUB*. The row *Iteration* and *Time* denote the number of iterations and the time (in seconds) for solving each instance by our combinatorial auction approach.

Table 1: Results for the first set of fifteen instances.

Quantity ≤ 2	1	2	3	4	5
Opt	2431.5	2516.2	2602.6	2348.1	2279.2
Time (s)	141	690	402	101	116
CAFLB	2431.5	2516.2	2426.4	2348.1	2279.2
CAFUB	2431.5	2516.2	2616.23	2348.1	2279.2
Gap (%)	0	0	7.8	0	0
Iteration	58	90	81	50	66
Time (s)	450	1278	1423	514	936
Quantity ≤ 5	6	7	8	9	10
Opt	2618.7	2536.9	2499.7	2398.2	2426.9
Time (s)	275	7200	836	1858	1672
CAFLB	2618.7	2536.9	2499.7	2398.2	2426.9
CAFUB	2618.7	2536.9	2499.7	2398.2	2426.9
Gap (%)	0	0	0	0	0
Iteration	81	72	45	73	152
Time (s)	1761	41772	7850	9006	7061
Quantity ≤ 10	11	12	13	14	15
Opt	2138.2	2173.7	1947.6	2211.7	2504.7
Time (s)	961	7200	590	7200	7200
CAFLB	2138.2	2173.7	1947.6	2211.7	2504.7
CAFUB	2138.2	2173.7	1947.6	2211.7	2504.7
Gap (%)	0	0	0	0	0
Iteration	81	68	49	75	54
Time (s)	3891	32915	1911	44702	42243

From the above two tables, we can see that our combinatorial auction approach can find a globally optimal solution for most instances except for instances no. 3, no. 22, and no. 25. For the three instances, our approach can find a fairly good solution.

Table 2: Results for the second set of fifteen instances.

Quantity ≤ 2	16	17	18	19	20
Opt	502.9	965.9	881	1314.4	514.9
Time (s)	2308	292	44	62	1000
CAFLB	502.9	965.9	881	1314.4	514.9
CAFUB	502.9	965.9	881	1314.4	514.9
Gap (%)	0	0	0	0	0
Iteration	49	82	85	58	83
Time (s)	10266	4098	697	338	2246
Quantity ≤ 5	21	22	23	24	25
Opt	2445.4	816.8	380.1	690.2	1233.6
Time (s)	776	128	2250	3914	705
CAFLB	2445.4	707.7	380.1	690.2	1082
CAFUB	2445.4	838.701	380.1	690.2	1266.9
Gap (%)	0	18.5	0	0	17.1
Iteration	52	115	62	54	56
Time (s)	9376	2696	17232	35113	992
Quantity ≤ 10	26	27	28	29	30
Opt	651	746.5	95.2	706.1	1062.4
Time (s)	5936	406	110	291	6359
CAFLB	651	746.5	95.2	706.1	1062.4
CAFUB	651	746.5	95.2	706.1	1062.4
Gap (%)	0	0	0	0	0
Iteration	57	46	41	81	57
Time (s)	84407	13805	947	3960	50037

6 CONCLUSIONS

The carriers' collaboration problem in less than truckload transportation with pickup and delivery requests has been studied in this paper. A Lagrangian relaxation based price-setting combinatorial auction approach is proposed for the total profit maximisation of the alliance in the collaboration. Numerical experiments on thirty randomly generated instances demonstrate the effectiveness of the approach. The main advantage of our approach is that the decision marking of each carrier is made in an autonomous and decentralised way, there is no confidential information of a carrier revealed to other carriers, so the approach is more implementable than a centralised approach where all information is shared among the carriers. In our future work, we will design a fair profit allocation mechanism to keep the persistence of the collaborative alliance.

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