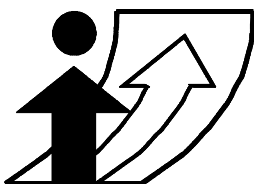


Combinatorial Auctions for Trucking Service Procurement: An Examination of Carrier Bidding Policies

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An Examination of Carrier Bidding Policies

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Abstract

Combinatorial auctions are increasingly used by large shippers as a method to establish service contracts with trucking companies. In order to achieve maximal benefits in these auctions, carriers must determine a bidding policy that can accurately evaluate the costs they will incur to fulfil these contracts and which can quickly examine many different possible options. In this paper, we analyze the complexity of this bidding problem for the procurement of truckload trucking service contracts; further, we propose an optimization-based approximation method to aid a carrier in constructing bids. Using a simulation framework, we examine the performance of this method relative to a straightforward bidding policy similar to those used in practice.

Keywords

Combinatorial auctions, bidding, contract procurement, trucking, set covering

Preferred citation

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1. Introduction

Combinatorial auctions are those in which a set of heterogeneous items are put out for bid simultaneously and in which bidders can submit multiple bids for combinations or bundles of these items. Bids can be structured and described with sophisticated logical relationships so that bidders can make conditional bids to properly express their preferences for different collections of items. An economically efficient price discovery mechanism, combinatorial auctions have received significant attention from computer scientists, operations researchers and economists in recent years. Further, these auctions have been used with apparent significant benefits in a variety of industries. Combinatorial auctions are especially suitable for multi-item auctions in which complementarities and/or substitution effects exist among different combinations of items and in which bidders have complicated preferences for bundles rather than for individual items. The procurement of trucking services is a typical example.

In trucking service procurement, shippers (typically large manufacturers and retailers) have a set of distinctive pickup and delivery orders with different origins and destinations. These origin-destination pairs are called lanes. Shippers sell service contracts to pre-screened carriers (trucking companies) based on transportation rates. An important factor contributing to a carrier's transportation rates is the empty movement costs incurred by repositioning vehicles. As a result, carriers will value a set of lanes more highly than the sum of individual lanes if they can reduce their empty movement costs by combining these lanes and constructing a continuous tour or by consolidating less-than-truckload loads. In recent years, shippers, aware of these characteristics of trucking operations, have begun to sell contracts to carriers in a single combinatorial auction instead of requesting quotes for each lane separately as was typically done in the past. This practice has reportedly resulted in significant benefits to shippers.

However, combinatorial auctions involve many inherently difficult problems. The problem of how to allocate bids among a group of bidders, known as the "winner determination prob-

lem”, has spurred much interest in operations research. Economists are designing new economically efficient mechanisms for combinatorial auctions to help reveal bidders’ true values. An even harder problem that has received less attention to date is the bid construction problem, which is, how bidders should compute their valuations over different combinations of items. In trucking service procurement, a carrier has to determine a bidding policy to evaluate different routing plans based on different combinations of lanes and to construct their bids accordingly in order to maximize their opportunities and benefits. Large carriers may need to construct many bids each month and typical bid construction methods are based primarily on historical experience. In addition to being very time consuming, these methods for generating bids may miss out on many opportunities.

In this paper, we first review applications of combinatorial auctions in freight transportation service contract procurement and discuss related research. This is followed by an introduction of the carrier’s bidding problem and a discussion of its complexity and the current practice of generating bids. We then propose an optimization-based approximation bidding method and examine its performance, relative to simple, straightforward bidding policies using a simulation analysis.

2. Literature Review

In recent years, there has been a surge of interest in the design and use of combinational auctions across many applications (de Vries and Vohra, 2001). In these auctions, multiple items are traded simultaneously in a single auction and more importantly, each item is treated as an independent unit and bidders are allowed to bid for their desired combinations of these items. In more sophisticated cases, bidders are able to make structured or conditional bids with complex logical expressions. For instance, a bidder can ask for an exclusive-or (XOR) bid of two items, which simply means it would accept any one of these two items for their respective bidding price but not both. We call these two items substitutable to this bidder. A set of

items can also be complementary to a bidder if it bids for a combination of these items as a whole.

In trucking operations, carriers have complicated synergies over different combinations of contracts; as a result, combinatorial auctions are a particularly suitable resource allocation mechanism for trucking service procurement. The basic unit in shipper-carrier transaction is called lane, which is simply an origin-destination pair with delivery demand. Traffic lane operations exhibit strong interdependencies, that is, the cost of serving one lane for a carrier is greatly affected by its opportunity to serve other lane(s). Specifically, the cost of serving a set of lanes together may be less than, equal to and more than the cost of serving them by separate carriers. For example, a lane from Miami to New York is not related to a lane from Los Angeles to San Francisco; as a result, it does not make a difference if they are contracted them to two carriers separately or to a single carrier in terms of operation costs. However, a lane from Los Angeles to Las Vegas is complementary to a lane on the return trip from Las Vegas to Los Angeles which makes the combination of operations more cost-effective; meanwhile, another lane from Las Vegas to Los Angeles could be a substitute to the direct return trip. This property of freight transportation operations is known as “economies of scope” and was the subject of extensional examination by Caplice (1996). This property contributes to the carrier’s complicated valuations. In a conventional procurement method, shippers either request for quote for each separate lane, or ask for a total price. Carriers lack the tools to fully leverage this property to optimize their operations and tend to bid high in order to cover additional empty movement costs. As a result, a part of this cost increment is passed to shippers and a higher procurement cost is incurred.

Recently, large shippers observed this property and started to experiment with combinatorial auctions with the intention to give carriers flexibility in bidding and eventually to reduce the shippers’ own procurement costs. In addition, shippers hope to gain benefits such as a reduction in the size of their carrier base. Sears Logistics may have been the first to use combinatorial auctions to procure truckload trucking services from carriers. Ledyard et al. (2002) reported that in 1995, Sears Logistics Services, with the help of its consulting firms of Jos.

Swanson and Co. and Net Exchange, conducted a multi-round combinatorial reverse auction for the procurement of contracts of serving over eight hundred lanes (delivery routes) and involving a cost of nearly two hundred million dollars per year. Using their “combined value auction” method, Sears Logistics Services reported a 13% savings which reduced its transportation procurement cost by \$25 million per year. The Home Depot conducted a one-shot, sealed-bid combinatorial auction to procure services for its truckload shipments in 2000 with the aid of its partner i2 Technology (Elmaghraby and Keskinocak, 2002). In that application, the lanes that were auctioned-off accounted for about 52000 moves, approximately one fourth of all the inbound moves to stores within Home Depot’s network. Over 110 carriers were invited for participation and a majority of them submitted bids. The authors reported that “the new bidding process is a big success” and “Home Depot intends to continue to use this new bidding process”, but no specific savings figures were disclosed.

Additional applications of combinatorial auctions in the procurement of freight transportation contracts include those employed by Wal Mart Stores, Compaq Computer Co, Staples Inc., The Limited Inc. and many others (Elmaghraby and Keskinocak, 2002, Caplice and Sheffi, 2003).

While shippers can potentially reap huge benefits from the use of combinatorial auctions, several difficult problems emerge. The most obvious problem is the design of a bidding language, i.e., a syntax that is specified by auctioneers for bidders to express their logical preferences over combinations of bidding items. A “good” bidding language should both be expressive so that bidders are able to express their synergies on their desired combinations of items and be simple so that bidders can understand and use it easily. Rothkopf, Pekec and Harstad (1998) discussed the restricted structures of bids under different scenarios of combinatorial auctions so that the number of bids generated can be tractable. Nisan (2000) formally introduced eight combinatorial bids including or extending from three basic types: atomic bids in which a bundle of items are treated as a single bid with an all-or-nothing relationship; OR bid which is a collection of atomic bids in which the bidder will serve any number of disjoint atomic bids for the sum of their respective prices; and, XOR bid in which the bidder will

serve at most one out of a set of atomic bids at the specified price. He further demonstrated that a combination of these basic types of bids such as OR-of-XORs or XOR-of-ORs can represent all possible valuations of bidding items with different complexities. Abrache et al (2003) discussed the limitation of Nisan's language and proposed a new two-level bidding framework.

The winner determination problem, the problem of assigning winning, non-conflicting bids to bidders with maximal benefits, has received the most attention in the research related to combinatorial auctions. It can be formulated as a variant of either the set covering problem or the set partitioning problem or the set packing problem depending on the auction format and is NP-complete in all cases. Both exact and approximation algorithms have been studied in the past for the winner determination problem, mostly from a re-discovery of past algorithms for the set packing (covering, partitioning) problem. A detailed review of formulations and these algorithms can be found at de Vries and Vohra (2001).

The auction mechanism design problem, the question of how to specify auctions formats and rules in order to induce participants to bid at their true reservation values and achieve economic efficiency, has been a topic of interest in auction theory for many years. However, few scholarly papers considered the design of combinatorial auctions until most recently. One new problem generated by combinatorial auctions is the threshold problem. It is a variant of the free-rider problem and occurs when small bidders fail to coordinate their bids to beat large but inefficient bids because each of these small bidders will have an intention to bid less and anticipate other bidders to bid high so that they by themselves can be a "free rider" (Cramton, 2002). Bykowsky, Cull and Ledyard (2000) and DeMartini et al. (1999) proposed new designs to avoid this problem and achieve economic efficiency. In addition, Parkes and Ungar (2000a, 2000b) discussed the design of iterative auctions to reduce the complexity of the winner determination problem and analyzed their equilibrium conditions.

All of these problems are from an auctioneer's perspective. A classic assumption in auction theory is that bidders know their true values for the items that they want to bid prior to the auction (known as their private value) or the value is common across all agents but unknown due to missing information (known as common values) (McAfee and McMillan, 1987). However, this assumption does not hold any more in a combinatorial auction, especially when a large number of combinatorial opportunities exist and when bidders have hard local optimization problems to solve. This causes a potentially hazardous gap in combinatorial auction theory. Larson and Sandholm (2001) showed that the Generalized Vickrey Auction protocol loses its dominant strategy property when bidding agents have free but limited computational resources. Conen and Sandholm (2001) observed the existence of an exponential number of bundles that bidders may need to compute. Further, Parkes, Ungar and Foster (1999) introduced a bounded-rational compatible auction in which a bidding agent makes bidding decisions based only on approximate information about the value of a good, that is, lower and upper bounds on its true value.

In trucking service procurement using combinatorial auctions, a carrier also has very hard bidding problem to consider. This problem has not been addressed in the past. We describe this problem and analyze its complexity in the next section.

3. Problem Statement

Consider a trucking company bidding in a combinatorial auction for contracts to serve a set of new lanes. We first define the relevant notation that will be used throughout this paper.

In a transportation network $G(V, A)$, a lane is an origin destination pair that may include one or more intermediate nodes in V . We use AB to denote an empty lane from node A to B which might be used to connect loaded moves or for equipment repositioning, \overline{AB} represents

a new lane with delivery demand. We also use \overline{ACB} to denote a new lane from A to B via intermediate node C.

Further, a bid b_n is a pair consisting of a set of lanes S_n with a bid price p_n . A single-item bid contains only one new lane. A route is a sequence of nodes starting and ending at the same location that satisfies all operational constraints. A set of lanes can be constituents of this route and it is natural to generate an atomic bid from these new lanes and to bid for them as a whole. We also use $b_i \cap b_j$ to denote the set of common lanes shared by bid b_i and b_j (in fact route i and j).

A carrier's values and preferences over a set of new lanes and different sets can be strongly interdependent. As described in Song and Regan (2003), we have the following definition.

Definition: Denote $v(S_i)$ as a carrier's true cost of serving a set of new lanes S_i if and only if these lanes are awarded, we say two disjoint sets of new lanes S_i and S_j are:

Complementary: if $v(S_i) + v(S_j) > v(S_i \cup S_j)$;

Substitutable: if $v(S_i) + v(S_j) < v(S_i \cup S_j)$;

Additive: if $v(S_i) + v(S_j) = v(S_i \cup S_j)$;

We give examples for each of them. If a carrier bids for new lanes \overline{AB} and \overline{BA} , they are *complementary* to each other since bundling them together as an atomic bid incurs minimal empty movement cost. Now suppose there is another new lane \overline{BCA} , then we can see that bids $\{\overline{AB}, \overline{BA}\}$ and $\{\overline{AB}, \overline{BCA}\}$ are *substitutable* with respect to \overline{AB} since serving all three

lanes will incur an empty movement cost in AB . *Additive* relationships exist between any two bids with no common new lanes.

An OR-of-XOR bidding language as described in Nisan (2003) is used in this paper to express these logical preferences, that is, a mixture of atomic, OR and XOR bids. It is observed that additive logical relationships can be efficiently expressed by OR bids, and substitutable logical relationships can be represented by XOR bids with the number of these equal to the number of atomic bids.

Now in a combinatorial auction with these definitions, the bid construction problem is that of evaluating a carrier's relative preferences over different combinations of new lanes and how to generate bids accordingly. Note that the resulting bids consist of three basic elements: the collections of bidding lanes, a carrier's reservation price for each collection, and the logical relationships between and among these collections. Further, the following assumptions are made.

Each carrier is given the details of new service contracts including the forecast demand and lane details. In this research we consider only the truckload trucking problem in which each load must be moved directly to its destination before the vehicle can perform any other deliveries. We assume that repositioning a vehicle from the destination of one lane to the origin of another lane incurs an empty cost proportional to the distance travelled and that travel time on each lane is proportional to distance. We also assume that trucks are available at any location at the beginning of the auction, that is, there is no central depot, and carrier's capacity is unlimited. This assumption is reasonable for both long-haul trucking operations and local and regional operations in which carriers bid only for lanes in their domicile region. We further assume that carriers do not consider future demands during the auction process.

The carrier's objective in such an auction is to find an effective policy for estimating their true costs and preferences over any combination of new lanes and hence construct their bids accordingly in order to win the lanes most profitable for them. Note that the carrier's objective is not to win as many lanes as possible. Instead, a carrier wishes to obtain lucrative contracts on lanes on which its operation can be efficient. Finally, each carrier's valuation is considered proprietary. Carriers do not know their competitor's bidding strategy or attempt to compute their valuations, and their competitors also do not compute their competitor's valuations and so on.

As discussed in Song and Regan (2003), a carrier needs to evaluate an exponential number of combinations in the worst case and the valuation on each of these combinations involves solving an NP-complete problem which can be modelled as a vehicle routing and scheduling problem. This makes the bid construction problem extremely complicated. In practice, even large carriers lack the optimization-based bidding decision support tools to aid them in preparing bids in order to incorporate their synergies and maximize their bidding benefits. Instead, they are struggling with these decisions and use simple straightforward methods as a bidding policy based on historical data and their personal knowledge. While these simple methods are intended to incorporate synergies by identifying combination opportunities among new lanes, they are from a local optimization viewpoint and do not consider logical relationships between these combinations. In the following, we propose an optimization based approximation method and compare its performance with the simple bidding policy.

4. Bid Construction in the Absence of Pre-Existing Commitments

In this paper we address a simplified situation in which carriers either do not have any pre-committed contracts of current lanes, or they do not intend to integrate new lanes into their current operations. Hence, they are only interested in the combination opportunities among new lanes. This is not unusual in practice as large carriers will run dedicated sub-fleets as-

signed to individual (large) shippers. We first argue that a carrier does not need to express his XOR bids explicitly under such circumstances, given the constraints defined in the winner determination problem. As such, OR bids are sufficient to express a carrier's preferences with acceptable complexity, which makes the size of bid sets manageable and also reduces the complexity of the winner determination problem. The reason is the following:

Suppose in a reverse combinatorial auction, a carrier generated a number of atomic bids $\{b_1, b_2, \dots\}$, and that each bid contains a subset of new lanes with or without empty lanes for connection purpose. If $b_i \cap b_j$ contains only empty links, then obviously b_i and b_j are additive and a carrier can commit to either or both of them if awarded contracts. If $b_i \cap b_j$ contains a common set of new lanes, that is, b_i and b_j are substitutable with respect to that set of new lanes, then a carrier can only commit to one of them even if it submits both, hence it makes a $\{b_i\} XOR \{b_j\}$. However, since the shipper's winner determination problem restricts each new lane to be assigned to one and only one bid, a carrier does not need to indicate this XOR relationship between b_i and b_j in an explicit way.

Observation 1: *XOR logical constraints can be replaced with OR constraints without increasing the bid size when carriers do not have any pre-existing commitments of current lanes to protect.*

Next we propose a strategy to generate bids for carriers in which combinational bids consisting of bundles of new lanes are favoured against single-item bids in which each bid only contains a single new lane. The idea is straightforward: we make carriers construct bids in such a way that the total operating empty movement cost is minimized. This essentially requires solving a truckload vehicle routing problem. One important approach for solving the vehicle routing problem is to formulate this problem as a set partitioning problem and to then use a column generation method to obtain exact solutions (Desrochers et al., 1992, Bramel and

Simchi-Levi, 1997). We follow a similar approach due to some important and nice features that can be derived from that formulation.

The first step of this bidding strategy involves using an exhaustive search algorithm to enumerate all routes with respect to routing and time window constraints and treat each of them as a decision variable in the set partitioning formulation. For example, a depth first search algorithm can be applied to find all routes satisfying the following constraints:

A route does not visit one location more than once;

If time windows are considered, a lane's delivery schedule has to match the subsequent lane's pick-up time; Note that in general, the lanes do not have associated time windows;

No two empty lanes can occur consecutively in a route (these would be replaced by a single direct empty move);

Other operational constraints such as maximum route distance or driver work rules may be applied.

In this process each new lane is duplicated such that it can be used as an empty lane by other routes. And each route constitutes a candidate bid $y_j \in \varpi$: the new lanes in this route form the set of bidding items and its reservation cost can be calculated based on route length, empty movement cost and a carrier's profit margin (Song and Regan, 2003). We associate an empty movement cost e_j with each bid y_j that is equal to the total empty movement cost of that route. We feed these candidate bids as decision variables into a Set Partitioning Problem formulation of the Bid Construction Problem (BCP-SP) as follows:

BCP-SP

$$\text{Min} \quad \sum_{j=1}^J e_j y_j \quad (1)$$

$$\text{s.t.} \quad \sum_{j=1}^J b_{ij} y_j = u_i \quad \forall i \in I \quad (2)$$

$$y_j = 0, 1 \quad (3)$$

$$b_{ij} = \begin{cases} 1 & \text{if new lane } i \text{ is in bid } j \\ 0 & \text{otherwise} \end{cases}$$

Where y_j is a binary decision variable or candidate bid in set J , if a lane involves multiple loads, y_j is an integer instead; i is a new lane in set I , and u_i is the number of loads on that lane. The objective function minimizes the total empty movement cost under an optimal allocation of lanes, the first constraint guarantees that each lane will be served by exactly one route. Suppose the optimal solution to this problem is $\varpi^* = \{y_j^*\} \subset \varpi$. Note the number of optimal routes in a solution may exceed a carrier's fleet capacity. However, this problem can be addressed by restricting the number of routes selected to be equal to or less than that carrier's fleet size. Also note that in practice, large trucking companies regularly contract for more routes than they can serve and will sub-contract excess demand as needed.

We observe that an optimal solution y_j^* to the BCP-SP problem has three important features: first, each new lane i is covered only by one optimal bid y_j^* so that any two optimal bids are mutually exclusive of new lanes.

Second, combinational bids consisting of collection of new lanes are favoured against single-item bids when complementary relationship exists between these lanes. For example, given two new lanes \overline{AB} and \overline{BA} , a carrier could have three potential bids: $\{\overline{AB}, \overline{BA}\}$, $\{\overline{AB},$

$BA\}$, $\{AB, \overline{BA}\}$. Certainly the first bundled bid is the optimal solution. This implies that a carrier would like to take risks to bid for combinational bids in this strategy.

Finally, this formulation guarantees that even if only a subset of submitted bids $\varpi^* = \{y_p, y_q \mid p \in P, q \in Q, P, Q \subset J\}$ is awarded by the shipper, that subset will still form an optimal solution to this carrier's vehicle routing problem. The proof is given as below:

Proof: Now assume that after carriers submit the optimal bids in ϖ^* and shippers solve the winner determination problem to allocate bids, this carrier is only awarded a subset of ϖ^* , that is, $\varpi' = \{y_p \mid p \in P, P \subset J\} \subset \varpi^*$. Without loss of generality, we assume that this carrier will only lose those new lanes $m \in M$ and that each lane contains at most one truckload. Denote the load on lane i by u_i , then the BCP-SP problem before auction can be rewritten as follows and its optimal solution is $\{y_{j \setminus p, q} = 0, y_p = 1, y_q = 1\}$. The first set of constraints guarantees that each new lane not awarded to this carrier is covered by some candidate route since carriers bid for all lanes. Constraint (6) guarantees those new lanes that eventually will be assigned to this carrier are also included in some routes. These routes could be any one in y_j , however, in the optimal solution, only one of them will be selected.

$$\text{Min} \quad \sum_{j \setminus p, q}^J e_j y_j + \sum_p^P e_p y_p + \sum_q^Q e_q y_q \quad (4)$$

$$\text{s.t.} \quad \sum_{j \setminus p, q}^J b_{ij} y_j + \sum_p^P b_{ip} y_p + \sum_q^Q b_{iq} y_q = u_i \quad \forall i \in I \ \& \ i \neq m \quad (5)$$

$$\sum_{j \setminus p, q}^J b_{mj} y_j + \sum_p^P b_{mp} y_p + \sum_q^Q b_{mq} y_q = u_m \quad \forall m \in M \ \& \ M \subset I \quad (6)$$

$$y_j, y_p, y_q = 0, 1 \quad (7)$$

$$b_{ij} = \begin{cases} 1 & \text{if new lane } i \text{ is in bid } j \\ 0 & \text{otherwise} \end{cases}$$

After shippers assign bids, the formulation for the carrier's routing problem is similar to this except that some rows (lanes) and columns (bids) are eliminated. In addition, the decision variables in the post-auction problem are just a subset of those in the original pre-auction problem due to the fact that the same route search criteria are performed. Then we only need to prove that with the loss of bids y_q , the post-auction BCP-SP problem has an optimal solution of $\{y_{j \setminus p} = 0, y_p = 1\}$.

Recall the first feature of our bid generation strategy is that all optimal bids are mutually exclusive of new lanes, hence if the carrier does not win bid y_q , it loses all new lanes included in y_q . That is, $b_{mq} = 1$ and $b_{iq} = 0, \forall i \neq m$. Therefore, since $\{y_p = 1, y_q = 1\}$ is feasible to the pre-auction BCP-SP problem, $\{y_p = 1\}$ also satisfy constraint (5) in the post-auction BCP-SP problem. Also since those new lanes $m \in M$ considered in constraint (6) will not be awarded to this carrier after auction as we assumed, constraint (6) no longer exists in post-auction problem, and $\{y_p = 1\}$ is a new feasible solution to the resulting BCP-SP problem.

Now we prove $\{y_p = 1\}$ is also optimal for the post-auction BCP-SP problem. Assume the optimal solution to the new BCP-SP problem is $\{y_{p'} = 1, p' \in P' \& P' \neq P\}$ with an empty cost

$\sum_{p'} e_{p'} < \sum_p e_p$. Then by adding y_q , a new set of bids $\{y_{p'}, y_q\}$ is a feasible solution to the

original pre-auction BCP-SP problem. Further, its total empty cost

$\sum_{p'} e_{p'} + \sum_q e_q < \sum_p e_p + \sum_q e_q$, this contradicts the fact that $\{y_{j \setminus p, q} = 0, y_p = 1, y_q = 1\}$ is the op-

timal solution. **(End of proof)**

This last feature of our strategy is a very important and favourable one in that optimal bids constructed using this strategy always minimize a carrier's empty movement cost regardless of the outcome of auction and also are independent of other competitors' bidding strategies.

Observation 2: *Optimal bids generated from outcomes of the BCP-SP strategy minimize carriers' operating cost even if only a subset of bids are awarded, hence these bids are optimal regardless of its competitors' bidding strategies and the shipper's allocation rule.*

However, this bid construction strategy could omit some important bidding opportunities for substitutable bids due to its strict constraint that all bids are mutually exclusive of new lanes. Take the following for example: assume that there are three new lanes for bid: \overline{AB} , \overline{BA} and \overline{BCA} . Using the above strategy, a carrier will generate these optimal bids: $\{\overline{AB}, \overline{BA}\}$, $\{\overline{BCA}, AB\}$ with a total empty cost equal to $cost(AB)$. Now if this carrier loses \overline{BA} in an auction, it will automatically lose \overline{AB} , moreover, there is a good chance that it will also lose \overline{BCA} since that bid incurs a large empty cost. In comparison, suppose that carrier makes an additional bid $\{\overline{AB}, \overline{BCA}\}$, then even if \overline{BA} is awarded to another bidder, it will have a very good chance to win \overline{AB} and \overline{BCA} . To explore this kind of bidding opportunities for substitutable bids, we relax the first constraint in the above BCP-SP formulation and remodel it as a Set Covering Problem:

BCP-SC

$$\text{Min} \quad \sum_{j=1}^J e_j y_j \quad (8)$$

$$\text{s.t.} \quad \sum_{j=1}^J b_{ij} y_j \geq u_i \quad \forall i \in I \quad (9)$$

$$y_j = 0, 1 \quad (10)$$

$$b_{ij} = \begin{cases} 1 & \text{if new lane } i \text{ is in bid } j \\ 0 & \text{otherwise} \end{cases}$$

The set covering problem has been well solved and many good algorithms are known to reach exact solutions quickly. A complete reference on this problem is provided by Balas and Padberg (1976). Observe that multiple equivalent optimal solutions can exist for this problem and each of them constitutes a set of equivalent optimal bids. The most frequently used algorithm for integer programming problems – the branch and bound algorithm or its variants, will stop searching when any optimal solution is found. In order to explore the multiple optimal solutions, we propose to use a modified branch and bound algorithm to force the solver to search until all optimal solutions are found.

Using this algorithm, the solution to the above example turns to be: $\{\overline{AB}, \overline{BA}\}, \{\overline{BCA}, \overline{AB}\}$. Note that this solution also possesses the last two features of the BCP-SP formulation, namely bundles of lanes are favored over single ones and the optimality of this method is guaranteed even if only a subset of submitted bids are eventually awarded by the shipper (proof omitted). In addition, the single-item bid $\{\overline{BCA}, AB\}$ was discarded in this solution – this might weaken this carrier's competitiveness, however, this can be easily modified using an augmentation step and this does not hurt the optimality of our solution since they do not conflict with each other:

Bid Set Augmentation Algorithm:

For each pair of substitutable bids $b_i : \{S_i, p_i\}$ and $b_j : \{S_j, p_j\}$

Find their common shared new lanes $S_i \cap S_j$;

Replace $S_i \cap S_j$ with the shortest empty lanes and form two new routes;

If that new route satisfies operational constraints

Add this route to the bid set;

Else

Regroup remaining new lanes into a feasible route and bid;

End Loop

In summary, different logical relationships are treated using this optimization based bid construction strategy. First, bids with additive logical relationships do not need special treatment; when a set of lanes are complementary, a bid bundling these lanes is included and single-item bids are discarded if not in the optimal solution; finally, substitutable bids are expressed with OR bids and completed in the bid augmentation step. This bid construction strategy can be summarized as follows:

Augment the original network by adding duplicating empty lanes for each new lane;

Search all routes satisfying the operational constraints;

Feed these routes into BCP-SC problem and solve it with modified branch and bound algorithm;

Construct optimal bids from the outcome of step 3;

Check substitutable bids and use the Bid Set Augmentation rule to detect additional bidding opportunities;

We have emphasized that the computational burden faced by bidders is a serious issue and can be a hurdle for the realization of combinatorial auctions. This optimization-based approximation method reduces the complexity of the bid construction problem significantly. The reduction in the number of submitted bids also simplifies the shipper's winner determination problem. Moreover, this strategy manages to discover those sets of lanes that are more lucrative and critical to a carrier's operation and discard those with less importance or simply bid for them at a higher price.

5. Simulation Analysis

In this section, we examine the performance of our proposed bid construction method relative to a simple bidding policy. The experiment consists of simulating combinatorial auctions under various conditions to evaluate the effectiveness of our proposed method. Our simulation follows the same simulation framework that was used in Song and Regan (2003), that is, we assume two bidding agents who represent two carriers respectively compete for a set of new lanes in a combinatorial procurement auction hosted by a shipper agent. The underlying transportation network, input data such as maximum cycle length and probability of tendering future demands and bid allocation rules remain the same. There are 21 nodes with 214 O-D pairs and each of them can be a potential lane. The shipper's objective is still to minimize their procurement costs with each new lane covered by one of these two carriers. Carriers, on the other hand, compete for lanes most profitable to them and hence are profit maximizers.

We use the relative gains between two bidding agents to evaluate the performance of our proposed bid construction method. This is due to the reason that the complexity of the bidding problem prohibits the development of an explicit measurement of performance or a closed form numerical analysis. In reality, the outcome of an auction depends on many endogenous and exogenous factors such as the bidders' risk taking behavior and auction rules. If all bid-

ders make bids with the same policy, the combinatorial auction might get to an equilibrium solution or lead to nowhere; however, this is beyond the research scope of this paper.

In this simulation work, we assume that one bidding agent, which we refer to as the smart agent, uses our proposed optimization based bid construction method, and that another one, referred to as the simple agent, uses the simple straightforward bidding policy as described in Song and Regan (2003) to make bids. The key point in that method is to use a depth first search algorithm to seek opportunities to combine two or more lanes into a single operation with minimal empty costs and to bid for them as a whole, however, each new lane is bid only once and logical relationships between these combinations are not considered. To be more explicit, the simple agent searches for the following combinations of lanes in the order in which they are mentioned here: those involving four loaded lanes, those involving three loaded lanes, those involving two loaded lanes, those involving three loaded lanes and an empty lane, those involving two loaded lanes and an empty lane and those involving a single loaded lane and an empty lane.

In the simulation, if two agents submit the same bid, that bid will be assigned between them randomly. In our simulation, the set of new lanes is generated randomly over candidate O-D pairs and we examine the circumstances where the density of new lanes ranges from 0.1 to 0.9, i.e., the number of new lanes vs. the total number of candidate O-D pairs. Each bidding agent will bid for all these new lanes. In each iteration, the shipper provides the new lanes to these bidders and each of them makes their bids based on their own bidding strategy. Another assumption here is that each bidder will bid for their true reservation costs and that they have the same pricing method and profit margins. The main program is implemented with C++ and all integer programming problems involved are solved using CPLEX 8.0, however, the modified branch and bound algorithm used in the proposed bid construction strategy is coded with an imbedded CPLEX solver. This is necessary in order to find all candidate optimal solutions.

The results are promising. From Figure 1, we can see that the smart agent using the optimization based bidding strategy wins most of new lanes in every circumstance, while the simple agent can hardly compete. This suggests that the proposed bid construction method can combine bids in a more competitive way and is more powerful in terms of market penetration.

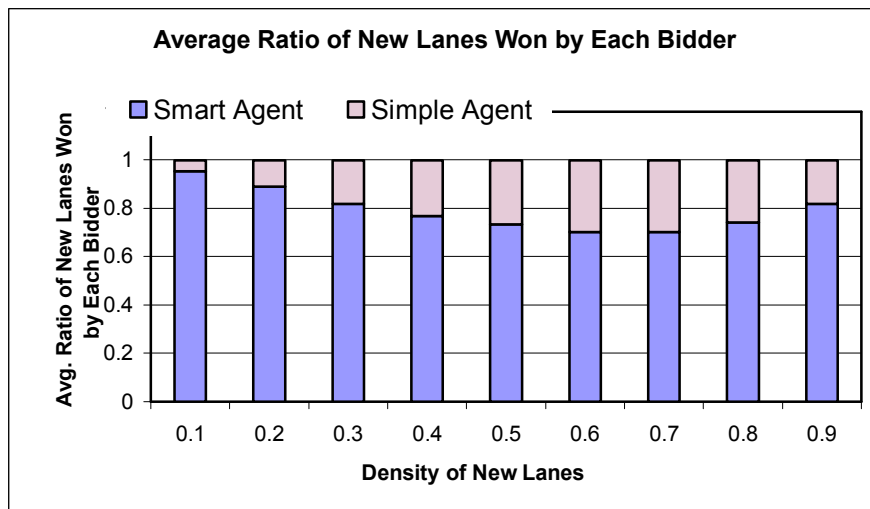


Figure 1 Ratio of New Lanes Won by Each Bidding Agent

Further, we calculate each carrier's optimal operating cost for the set of lanes they win, and compare their empty movement cost ratio which is the total empty cost under optimal operation versus the total movement cost including empty and loaded lanes. This indicator measures whether those bids constructed by the proposed bidding policy consist of more profitable lanes; that is, whether the lanes won constitute favourable operations for the carrier.

As Figure 2 indicates, both agents' empty cost ratios decrease with the increase of the density of new lanes, which is natural because more new lanes means more matching opportunities. It is also observed that smart agent's empty movement cost ratio is less than that of simple agent in almost all cases, and this gap increases with the increase of the density of new lanes. There is an exception that the smart agent has a higher empty movement cost when the den-

sity of new lanes is very low, however, it should be noted that when there are only few new lanes for bid, the chance for simple agent to win over smart agent is very slim and the simulation results reveal that in these cases simple agent often wins nothing and hence has no empty movement costs.

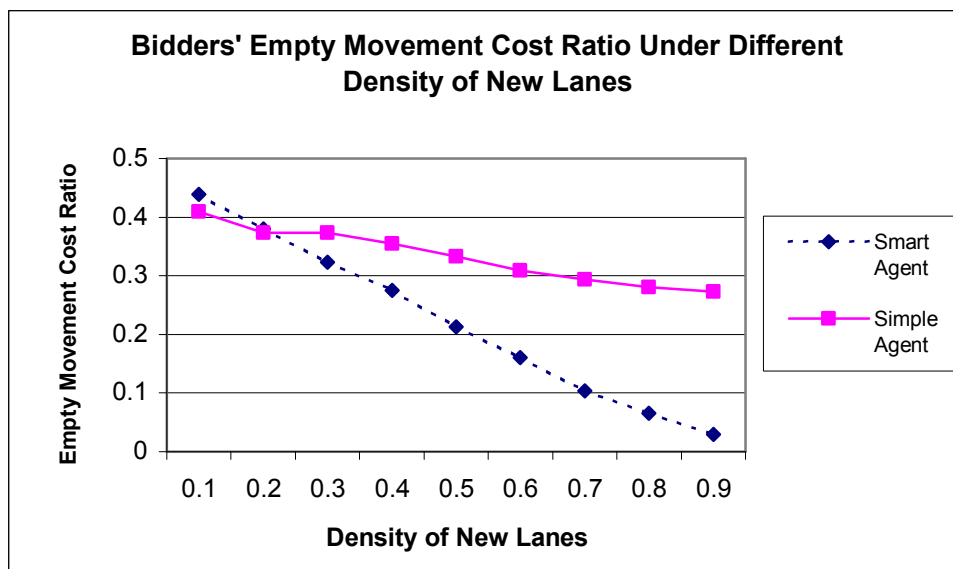


Figure 2 Bidders' Empty Movement Cost Ratio under Different Density of New Lanes

In summary, we can conclude that the proposed optimization based bid construction method does outperform the simple bidding policy and the benefits increase with the density of new lanes.

6. Conclusion

In this paper, we investigated the bidding problem in combinatorial auctions for the procurement of trucking service contracts from a carrier's perspective. We recognized the complexity of this problem and the lack of bidding decision support tools in carrier operations. As a result, an optimization-based bid construction strategy was proposed for situations in which

carriers do not have pre-existing commitments to other contracts. Our analysis proved that the proposed strategy is optimal for carriers in terms of operational efficiency.

Further, we examined the performance of our method relative to a simple straightforward bidding policy that only incorporates synergies between lanes partially but does not consider the complicated logical relationships between combinations. Through a simulation study, we illustrated that our method outperforms the simple bidding policy and that the benefits increase with an increase in the number of new lanes.

Most research in auction theory to date is based on the assumption that bidders or carriers know their own values or costs a priori and that they construct their bids accordingly. However, this assumption does not hold in combinatorial auctions where bidders have hard valuation problems to solve. In particular, a bidder needs to consider an exponential number of combinations in the worst case and needs to compute many NP-hard sub-problems. In this paper, we proposed a bidding strategy in which carriers are capable of constructing bids in an optimal way and in which this NP-hard problem is only solved once.

Though specifically aimed at the carrier's bidding problem in combinatorial auctions for the trucking service procurement, we believe this methodology can be extended to broader fields where similar properties exist among bidding items in combinatorial auctions.

Extensions of this work include the consideration of more complicated cases where pre-existing commitments exist and carriers need to consider routing plans between new lanes and current lanes in addition to combinations among new lanes themselves. The model developed in this research assumed the size of candidate bids in the set covering problem is manageable, when this does not hold, other heuristic techniques should be developed. The bidding problem in combinatorial auctions is a new research arena and there are many new and complex problems that attract interests from researchers in a variety of fields.

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