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**Approximation Algorithms for the Bid Construction Problem in Combinatorial  
Auctions for the Procurement of Freight Transportation Contracts**

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**Abstract**

The bid valuation and construction problem for carriers facing combinatorial auctions for the procurement of freight transportation contracts is very difficult and involves the computation of a number of NP-hard sub problems. In this paper we examine computationally tractable approximation methods for estimating these values and constructing bids. The benefit of our approximation method is that it provides a way for carriers to construct optimal or near optimal bids by solving a single NP-hard problem. This represents a significant improvement in efficiency. In addition, this method can be extended to many other applications.

**Keywords**

Combinatorial auctions, contract procurement, set covering, trucking operations

Transportation Research, Part B, Methodological, under review

## **Introduction**

Combinatorial auctions are those in which the auctioneer places a set of heterogeneous items out to bid simultaneously and in which bidders can submit multiple bids for combinations of these items. Further, bids can be structured so that bidders can express their desire for a bundle of inseparable items (known as atomic bids), a collection of bids with additive values (known as OR bids) or a collection of atomic bids which are mutually exclusive (known as XOR bids). Our research investigates how sets of bids should be constructed in such an auction so as to optimize the efficiency of the auction from the perspective of an individual bidder. While combinatorial auctions have many applications, of primary interest to our research is the procurement of contracts for freight transportation services.

In the past, when shippers (typically large manufacturing companies or retailers) needed to procure transportation services for a set of distinctive delivery routes (called lanes) with different origins and destinations or delivery schedules, they would obtain quotes on a lane-by-lane basis. That process can be modeled as a simple sealed bid reverse auction. However, recently shippers have begun to use combinatorial auctions for awarding service contracts.

In a freight transportation service procurement auction, carriers (trucking companies, or third party logistics providers) bid on contracts to move goods along pre-defined lanes for shippers. The pre-qualified carrier who submits the lowest bid is awarded the contract at the price bid. In this context, a carrier must determine the value of each contract as well as contract interdependencies in order to develop appropriate bids.

It is well known that the bid valuation and construction problem for carriers facing combinatorial auctions for the procurement of freight transportation contracts is very difficult and involves the computation of a number of NP-hard sub problems. Several recent researchers have examined the computational difficulties of the bidders'

valuation problem in these auctions (see for example Parkes, 2000). In this paper we examine computationally tractable approximation methods for estimating these values and constructing bids.

We first review research and practice related to combinatorial auctions and their application in the freight transportation industry. This is followed by a definition of the problem that must be solved and a discussion of the logical relationships between bids. We then investigate situations in which the bidding carriers do not have any pre-existing commitments to other contracts. We provide an approximation method for this problem based on solving a set covering problem and discuss some important features of this method. We further extend that strategy to circumstances where prior commitments exist and propose a modified branch-and-bound method to search for near optimal bids.

## **Literature Review**

The procurement of freight transportation services is a critical component for large shippers' logistics operations. In addition to their private fleets, shippers hire outside transportation companies under long or short-term contracts. It is estimated that in year 1997 the for-hire trucking industry alone contributed about \$92 billion to U.S. GDP (BTS, 1997).

In practice, most shippers follow a traditional procedure to procure transportation services including carrier screening, carrier assignment, load tendering and performance review (Caplice, 1996). Using this process, shippers attempt to reduce their costs and also to maintain a stable service levels under formal contracts. In addition, shippers use spot markets for occasional and spontaneous goods movement. Almost all assignments in these traditional transportation procurement modes are done in a lane-by-lane manner in which shippers select service providers for each individual traffic lane based on the price submitted by each carrier, or, a set of lanes are combined as a bundle and are considered inseparable. This procurement method can be modeled as a simple sealed-bid reverse auction and may be able to achieve economics of scale (Song and Regan, 2003).

However, this method ignores the economies of scope property that trucking operations are more sensitive to. A significant portion of trucking costs is due to the repositioning of empty vehicles from the destination of one load to the origin of a subsequent load. Traffic lane operations exhibit interdependencies, that is, the cost of serving one lane greatly depends on the opportunity of serving other lane(s). Caplice (1996) examined this economies-of-scope property and observed that traditional procurement methods does not properly account for this property. He suggested the use of combinatorial auctions for transportation procurement in which a carrier can bid based on the synergistic values of a set of lanes. As a matter of fact, large shippers have recognized this prior to that research and began to use combinatorial auction based procurement methods in the early 1990's. Ledyard et al. (2002) discussed the procurement of trucking services by Sears Logistics Services in 1995. That auction included over eight hundred service lanes and a cost of nearly two hundred million dollars per year. Sears Logistics Services, through its consulting firm of Jos. Swanson and Co. and Net Exchange, conducted a multi-round combinatorial reverse auction in which participating carriers were pre-selected so as to guarantee service levels and reported a savings of 13%. Most recently, using a large-scale simulation model, Song and Regan (2003) showed that combinatorial auctions should also benefit carriers by reducing operational costs at the same time as cutting shippers' procurement costs.

In addition to the trucking industry, combinatorial auctions have also been applied to other resource allocation problems in which complementarities and substitution effects exist among heterogeneous assets and in which bidders prefer bundles to single assets. These include but are not limited to auctions of wireless spectrum rights (Cramton, 2001), airport time slots (Rassenti, 1982) and network routing (Hershberger and Suri, 2001). A good survey of these activities can be found in de Vries and Vohra (2001).

Combinatorial auctions contain some inherent difficult problems. The auction mechanism design problem, the question of how to design auctions in order to induce participants to bid their true valuations and achieve economic efficiency, has been a topic

of interest in auction theory for many years. Bykowsky et al (2000) discussed the Federal Communications Commission (FCC) auction design problem and argued that simple auctions, including sequential single-item auctions and simultaneous independent auctions, are not suitable for resource allocation in which synergistic values exist. These methods either reduce auctioneers' revenue or expose bidders to financial risks by encouraging aggressive bidding. These researchers suggested that the use of combinatorial auctions is more economically efficient. However, there is no general equilibrium solution to combinatorial auctions. This type of auction also creates a new problem called a "threshold problem", which occurs when bidders bid less than their true valuation in order to pay less, at the risk of losing the auction. DeMartini et al. (1999) presented a new design for combinatorial auctions and discussed this problem.

An important question in the design of combinatorial auctions is how bids should be expressed. A successful bidding language must allow bidders to express synergistic values on their desired combinations of items. In addition, the bidding language should be efficient so that the number of bids will be tractable. Nisan (2000) introduced three basic types of bids: *atomic bids* in which a bundle of items are treated as a single indivisible bid; *OR bids* which are set of atomic bids in which the bidder will serve any number of disjoint atomic bids for the sum of their respective prices; and, *XOR bids* in which the bidder will serve at most one item in a set of atomic bids at the specified price. He illustrated that a combination of these basic types of bids such as OR-of-XORs or XOR-of-ORs can represent all possible valuations of bid items. Abrache et al (2002) pointed out that Nisan's bidding vocabulary is restrictive in that it cannot express such requests as "*select K among N items*" and is limited to indivisible goods. As a result, they proposed a two-level bidding framework to represent combined bids and analyzed its impact on the mathematical programming formulation of the allocation problem.

The winner determination problem, in which the optimal set of winning bids is identified, is known to be NP-complete and has attracted much attention. For example, Rothkopf, Pekec and Harstad (1998) presented a formulation equivalent to a set packing problem (As reminder to readers, when the inequalities in a set covering problem are

replaced by equalities the problem is called the set partitioning problem, and when the objective is maximization and all of the  $\leq$  constraints are replaced by  $\geq$  constraints, the problem is called the set packing problem.) Those researchers claimed that the manageability of combinatorial auctions depends upon the structure of permitted combinational bids rather than the number of bids. They also identified several special bid structures for which the winner determination problem is computationally manageable. de Vries and Vohra (2001) gave two formulations and reviewed the past approaches for tackling this problem, both by exact and approximation methods. Most of the past work deals with the single-unit case. Independently, Leyton-Brown, Shoham and Tennenholtz (2000) and Gonen and Lehmann (2000) provided a depth-first-search based algorithm embedded in a branch-and-bound framework to solve the multi-unit winner determination problem to optimal.

Most of the research mentioned above studied combinatorial auctions from the auctioneer's perspective and require that bidders or carriers know their true valuation on any combination of bid items (known as their private value) a priori, therefore they can structure and generate bids accordingly. However, this may not be true in practice, especially when a large number of combinations must be considered and in which bidders have hard local problems to solve. Parkes (2000) compared the auction performance for agents with hard local optimization problems and uncertain values for bid items. While acknowledging that market design cannot simplify the bidder's valuation problem alone, he argued that a well-designed auction could improve the quality of bidder's decisions. In another paper, Parkes, Ungar and Foster (1999) introduced a *bounded-rational compatible* auction in which a bidding agent makes bid decisions based only on approximate information about the value of a good, that is, lower and upper bounds on its true value. Conen and Sandholm (2001) observed the exponential number of bundles that bidders may need to compute and therefore proposed a design of an auctioneer agent that uses a topological preference structure to request only necessary information from bidders, and as a result, reducing the number of valuation problems that bidders need to solve. Further, they presented a method to make their design incentive compatible so that bidders only need to compute their own preferences. Recently, Song and Regan (2003)

pointed out that in the worst case a bidder must solve an exponential number of sub problems to identify their reservation prices and that each of these sub problems is NP-hard.

The bid construction problem may be even harder in the procurement of freight transportation contracts. In the trucking industry, carriers not only need to consider the economies of scope exhibited in delivery routes from new contracts, they also have to find an efficient way to integrate new contracts with their pre-existing commitments. This, normally modeled as a vehicle routing problem, is itself NP-complete in most cases as its solution typically requires the solution of variants of multiple traveling salesman problems. The solution of this problem provides a carrier's true valuation for a set of new contracts. Research on solving vehicle routing problems is common. Extensive reviews of the basic vehicle routing problem, time constrained routing and scheduling and dynamic and stochastic routing and scheduling can be found in Fisher (1995), Desrosiers et al (1995) and Powell, Jaillet and Odoni (1995), respectively.

Combinatorial auctions have been the topic of active research in the fields of operations research, computer science, economics and logistics during recent years. However, to the best of our knowledge, there has been no attempt to examine the bid construction problem from the perspective of bidders. Of particular interest are the following questions: How should carriers determine their true valuation for any bundle of lanes from new contracts? What is the optimal way to structure different combinations of new contracts? These questions are not easy to answer even for simple cases. In fact, carriers encounter much more complex optimization problems and decisions than do shippers in a combinatorial auction. In this paper, we examine these questions and propose approximation algorithms to solve them.



## Definitions

A lane is an origin destination pair that may include one or more intermediate nodes. We use  $AB$  to denote an empty lane from node A to B without any delivery request and only for connection or repositioning purpose,  $\overline{AB}$  to represent a new lane with delivery demand and  $\underline{AB}$  to denote a current lane with pre-committed contracts. We also use  $\overline{ACB}$  to denote a new lane from A to B via C.

1. A bid or atomic bid  $b_n$  is a pair consisting of a set of lanes  $S_n$  and its bid price  $p_n$ . A single-item bid contains only one new lane.
2. XOR logical relationship could exist among any number of atomic bids, implicit here is that this carrier is willing to serve at most one of this set of bids. OR logical relationship refers to that this carrier is willing to obtain any number of bids for the sum of their respective bid prices.
3. A route is a sequence of nodes starting and ending at the same location and satisfies all operational constraints. A route includes a set of lanes and is the basis to generate a bid.
4. 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).

## Problem Statement:

We consider trucking companies facing an invitation from a shipper to bid for contracts to serve a group of new lanes in a combinatorial auction. Each carrier is given the details of service contracts including: each lane's pickup location, the delivery location, the earliest pickup time, the latest delivery time and the number of full truckloads to be moved. Delivery time windows must be respected. In this research we consider only the truckload trucking problem in which the load must be moved directly to its destination before the vehicle can perform any other tasks. 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 traveled and that each lane's travel time is proportional to its distance. We assume that trucks are available at any location at the beginning of the auction and they can reside in any destination of a lane, that is, there is no central depot. This assumption is reasonable for long-haul trucking operations. 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 strategy for estimating their valuations on any combination of new lanes and hence construct their bids 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 that can make its current operation more efficient. This is particularly important when a carrier has pre-existing commitments to other contracts at the time of the auction. The complementary or substitution effects between new lanes themselves and between new lanes and currently contracted lanes complicate the matter and are expressed as logical relationships. Finally, each carrier's valuation is considered to be proprietary. Carriers do not know or attempt to compute their competitor's valuations.

### **Logical Relationships Between Bids:**

We use the same definitions of logical relationships between bids as in Song and Regan (2003):

*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 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 zero empty 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 cost in  $AB$ . Another example is when a carrier bids for new lanes  $\overline{BA}$  and  $\overline{BCA}$  given a current lane  $\underline{AB}$ , in this case  $\overline{BA}$  and  $\overline{BCA}$  are *substitutable* with respect to  $\underline{AB}$ . *Additive* relationships exist between any two bids with no common new or current lanes.

It is also 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. In the following we further discuss how to construct bids with respect to these logical relationships and use an OR-of-XOR bidding language (Nisan, 2000) to describe the bid relationships.

### **Bid Construction in the Absence of Pre-existing Commitments:**

In this context, carriers either do not have any pre-committed contracts or 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 themselves. We first argue that a carrier does not need to express his XOR bids explicitly under such a circumstance, given the constraints defined in the winner determination problem. As such, carriers only need to examine OR bids. 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 and/or empty lanes. 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 he submits both, hence it makes  $\{b_i\}XOR\{b_j\}$ . However, since 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 bid size when carriers do not have any pre-existing commitments of current lanes to protect from.*

Next we propose a strategy to generate bids for carriers in which bundles of lanes are favored against single-item bids. The idea is straightforward: we make carriers generate bids in such a way that the total operating empty cost is minimized. This essentially requires solving a truckload vehicle routing problem. One important method (Desrochers et al., 1992, Bramel and Simchi-Levi, 1997) for vehicle routing problem is to formulate vehicle routing problem as a set partitioning problem and to then use a column generation method to obtain exact solutions. We follow that approach due to some important features that can be derived from that formulation.

The first step of this strategy involves using a 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 *routes* satisfying the following constraints:

1. A route does not visit one location more than once;
2. A lane's delivery schedule has to match the subsequent lane's pick-up time;
3. No two empty lanes can occur consecutively in a route (these would be replaced by a single direct empty move);
4. 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  $y_j \in \mathbf{v}$ : the new lanes in this route form the set of bid items and its value can be calculated based on route length, empty cost and carriers' profit margin (Song and Regan, 2003). We associate an empty cost  $e_j$  with each bid  $y_j$  that is equal to total empty cost of that route. We provide these candidate bids into a Set Partitioning Problem formulation of 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. Suppose the optimal solution to this problem is  $\mathbf{v}^* = \{y_j^*\} \subset \mathbf{v}$ . 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. 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 the new lanes contained in any two optimal bids are mutually exclusive.

Second, bundles of new lanes are favored 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 bundles of lanes.

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

Now assume that after carriers submit the optimal bids in  $\mathbf{v}^*$  and shippers solve the winner determination problem to allocate bids, this carrier is only awarded a subset of  $\mathbf{v}^*$ , that is,  $\mathbf{v}' = \{y_p \mid p \in P, P \subset J\} \subset \mathbf{v}^*$ . Without loss of generality, we assume that this carrier will only lose those new lanes  $m \in M$  and 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  $\{y_{j \setminus p, q} = 0, y_p = 1, y_q = 1\}$ .

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

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

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

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

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

After shippers assign bids, the carrier's routing problem formulation 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 new lanes in all optimal bids are mutually exclusive, 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 constraint (6) no longer exists,  $\{y_p = 1\}$  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 obviously, 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 optimal solution. (End of proof)

This last feature of our strategy is very important in that optimal bids constructed by this strategy always minimize a carrier's empty 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 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 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 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*

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

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

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

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

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). We noticed 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 BCP-SP formulation (proof omitted). In addition, the single-item bid  $\{\overline{BCA}, AB\}$  is discarded which might weaken carriers' competitiveness, however, this can be easily modified using an augmentation step and this does not impact the optimality of the solution.

*Bid Set Augmentation:*

*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 shortest empty lanes and form two new routes;*

*If that new route satisfies operational constraints*

*Make a new out of this route;*

*Else*

*Regroup remaining new lanes into a feasible route and bid;*

*End Loop*

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

*Step 1. Augment the original network by duplicating empty lanes for new lanes;*

*Step 2. Search all routes satisfying operational constraints;*

*Step 3. Feed routes into BCP-SC problem and solve it with modified branch and bound algorithm;*

*Step 4. Construct optimal bids from outcome of step 3;*

*Step 5. Check substitutable bids and use Bid Set Augmentation rule to detect additional bidding opportunities;*

## Bid Construction in the Presence of Pre-existing Commitments:

In this section we extend the above bid construction strategy to the situation in which carriers have commitments for other contracts prior to the auction.

In such a context, two additional considerations have to be taken into account. First, new opportunities emerge from a combination of new lanes and current lanes; second, carriers' pre-existing routing plans might need to be protected. To explore new combination opportunities, we need to search combinations of new lanes and current lanes as well as opportunities among new lanes themselves at step 1 and 2 in the above bid construction strategy, and hence generate more candidate routes.

Next, we introduce these new opportunities into the BCP-SC formulation as follows:

*BCP-SC2*

$$\text{Min} \quad \sum_{j=1}^j e_j y_j \quad (11)$$

$$\text{s.t.} \quad \sum_{j=1}^j b_{ij} y_j \geq u_i \quad \forall i \in I \quad (12)$$

$$\sum_{j=1}^j b_{kj} y_j \geq u_k \quad \forall k \in K \quad (13)$$

$$y_j = 0,1 \quad (14)$$

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

$$b_{kj} = \begin{cases} 1 & \text{if current lane } k \text{ is in bid } j \\ 0 & \text{otherwise} \end{cases}$$

Note that now the set of candidate bids is  $J'$  and we have  $J \subset J'$ .  $I$  is the set of new lanes and  $K$  is the set of current lanes. From the outcome of this problem using the

modified branch and bound algorithm, additive and complementary logical relationships are treated as before.

However, XOR bids can no longer be ignored. Substitutable bids with respect to current lane(s) have to be examined and described with XOR logical relationships since the shipper's winner determination problem does not pose any constraints on current lanes. For example, a carrier who bids for two new lanes  $\{\overline{BA}, \overline{BCA}\}$  and has a current lane  $\underline{AB}$  could generate bids as follows:  $b_1 = \{\overline{BA}, \underline{AB}\}$ ,  $b_2 = \{\overline{BCA}, \underline{AB}\}$ ,  $b_3 = \{\overline{BA}, \underline{AB}\}$  and  $b_4 = \{\overline{BCA}, \underline{AB}\}$ . We can see that its valuations on  $\overline{BA}$  and  $\overline{BCA}$  are *substitutable* to each other with respect to current lane  $\underline{AB}$ , and they can not be submitted both to shipper using OR relationship since it will incur a loss if both bids are awarded. Hence we have the following observation:

*Observation 3: When valuations of two atomic bids are substitutable to each other with respect to a common set of current lanes, carriers need to submit both of them under an XOR logical constraint.*

As a result, the carrier has to use a bidding language such as OR-of-XOR to describe its preference. This makes the XOR logical relationship a critical decision in making bids.

In certain cases, XOR bids generated using this method could cause adverse results on carriers' bid decision. For instance, a carrier who has two current lanes  $\{\underline{AB}, \underline{BA}\}$  bids for a new lane  $\overline{BCA}$ , and generates two bids using the above bid construction strategy:  $b_1 = \{\overline{BCA}, \underline{AB}\}$ ,  $b_2 = \{\overline{BCA}, \underline{BA}\}$ . Suppose this carrier is awarded  $b_1$ , as a result, this awarded bid conflicts with this carrier's pre-existing routing plan before auction:  $\{\underline{AB}, \underline{BA}\}$ . The carrier will incur a loss under this flawed bidding strategy since it will offer a bid which cannot cover the empty backhaul cost. A more complicated situation occurs when the current routing plan includes a partial empty cost,

then the decision on whether to bid on a higher or lower price really depends on a few factors: carriers' risk taking behavior, new lane's relative profitability, and revenue and cost of current lanes relative to empty lanes.

In order to protect carriers' pre-existing routing plans prior to a combinatorial auction, an important rule is to exclude those routing plans from the current lane set at the time of the auction. In addition, one more condition must be added to the construction of atomic bids obtained from solving the BCP-SC2 problem:

*Bid Substitution Condition: Suppose  $b_i$  is a route consisting solely of current lanes with zero or relatively small empty cost and is in optimal solutions to BCP-SC2 problem, then for any bid  $b_j$  generated from solving BCP-SC2 problem, if  $b_j \cap b_i \neq \mathbf{f}$ ,  $b_j$  has to be substituted with a bid by replacing  $b_j \cap b_i$  with an empty lane.*

Still consider the above example, by exerting this condition, bid  $b_1 = \{\overline{BCA}, \underline{AB}\}$  shares a current lane  $\underline{AB}$  with pre-existing route  $\{\underline{AB}, \underline{BA}\}$ , hence this bid has to be replaced with bid  $b_2 = \{\overline{BCA}, AB\}$ .

We summarize the bid construction strategy in the context of pre-existing commitments as follows:

- Step 1. Augment the original network by duplicating new and current lanes;*
- Step 2. Search all routes satisfying operational constraints;*
- Step 3. Feed candidate routes into BCP-SC2 problem and solve it with modified branch and bound algorithm;*
- Step 4. Construct optimal bids from outcome of step 3;*
- Step 5. Check substitutable bids and use Bid Set Augmentation rule to complete bids;*
- Step 6. Apply rules in observation 3 for any two bids with common current lane(s) to develop XOR bids;*

*Step 7. Apply Bid Substitution Condition for any bid that conflict with pre-existing routing plans to exclude “bad” bids.*

## **Conclusion**

In this paper, we analyzed the bid construction problem that carriers need to solve to generate bids in a combinatorial auction for the procurement of freight transportation contracts. Optimization based strategies and the approximation algorithms were developed for situations in which carriers do and 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 in the first situation and near optimal in the second situation.

Most research to date is based on the assumption that bidders or carriers know their own valuations a priori and that they construct their bids accordingly. However, this assumption does not hold in many cases, and recently auction settings where bidders have hard valuation problems to solve are receiving more attention. 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 an approximation strategy in which carriers are capable of constructing bids in an optimal or near optimal way and in which this NP-hard problem is only solved for once.

Though specifically aimed at the carrier bid construction problem in combinatorial auctions for the procurement of trucking contracts, we believe this methodology can be extended to broader fields where similar properties exist among bid items in combinatorial auctions. This method is particularly robust in circumstances in which fewer candidate bids exist for the integer programming problem due to, for instance, complicated work rule structures.

Extensions of this work include empirical analysis to examine the robustness of the proposed strategy. The model developed in this research assumes that the size of candidate bids in the set covering problem is manageable, when this does not hold, other techniques such as column generation should be considered. Finally, from the point of view of overall freight transportation system efficiency, we point out that these auctions encourage competition between carriers that can lead to inefficiencies. These auctions would yield maximal efficiency only if carriers can develop collaborative relationships (Song and Regan, 2002).

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