Transportation Research Part B 65 (2014) 47–64

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Efficient auctions for distributed transportation procurement

Su Xiu Xu, George Q. Huang *

HKU-ZIRI Lab for Physical Internet, Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Hong Kong

ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form 22 March 2014
Accepted 22 March 2014

Keywords:
Distributed transportation procurement
Mechanism design
Efficient auctions
Primal–dual algorithm
Incentive compatibility

ABSTRACT

The purpose of this paper is to propose allocatively efficient auction mechanisms for the distributed transportation procurement problem (DTPP), which is generally the problem of matching demands and supplies over a transportation network. We first construct a one-sided Vickrey–Clarke–Groves (O-VCG) combinatorial auction for the DTPP where carriers are allowed to bid on bundles of lanes. The O-VCG auction minimizes the total transportation cost (i.e., *allocative efficiency*) and induces truthful bidding from carriers (i.e., *incentive compatibility*). To simplify the execution of auction, we next propose a primal–dual Vickrey (PDV) auction based on insights from the known Ausubel auctions and the primal–dual algorithm. The PDV auction is actually a multi-round descending auction that seems simple enough for bidders. The PDV auction realizes VCG payments and truthful bidding under the condition of *seller-submodularity*, which implies that the effect of each individual carrier is decreasing when the coalition increases. Such is the case for the DTPP in an oversupplied transportation market. The winner determination problem of O-VCG auction is solved by the proposed primal–dual algorithm when seller-submodularity holds. Finally, carriers may reveal less private information in the PDV auction due to its dynamic procedures.

1. Introduction

This paper aims to propose efficient auction mechanisms for the following version of the *transportation procurement problem* (TPP). Consider a transportation market with multiple origin–destination pairs (called *lanes*), one shipper and multiple carriers. The shipper has a set of indivisible shipments (called *items*), each defined by one full truckload, a lane, and a time window (typically pickup time and/or expected arrival time). The shipper seeks for an efficient procedure or mechanism through which the payment of transportation service would be minimized. The carriers, each of whom owns a set of vehicles, are available to meet the transportation demand. Each carrier is a rational, self-interested player who is trying to maximize his (potential) net utility, received payment minus cost. The total transportation capacity is assumed to be sufficient. Typically, the purchasing business is conducted by a third-party logistics service provider (e.g., logistics e-marketplace) on behalf of the shipper. Hence, the problem faced by the third party is to design and run an efficient mechanism that induces the minimal total transportation cost.

The carriers are allowed to ask for bundles of items. To reduce cost and improve the probability of winning items, carriers should build efficient movements with small empty mileage. Moreover, several operational constraints, such as routing and scheduling constraints, are often encountered in real-world applications. For example, a lane's delivery schedule has to match the subsequent lane's pickup time (i.e., scheduling constraint). Regarding routing constraints, it is often requested

* Corresponding author. Tel.: +852 95500297.
E-mail address: gqhuang@hku.hk (G.Q. Huang).

http://dx.doi.org/10.1016/j.trb.2014.03.005
0191-2615/

that: (i) a route does not visit one location more than once (i.e., a classic constraint of the *traveling salesman problem*) and (ii) no two empty lanes can occur consecutively in a route (e.g., Song and Regan, 2005). Hence, the problem faced by the carriers is to determine optimal *requests* (typically, *bids*) given the items and the trading mechanism, as well as the real-world operational constraints. The problem stated above is called the *distributed transportation procurement problem* (DTPP). Two significant characteristics of the DTPP are as follows: (i) transportation demands and supplies are distributed within a network and (ii) carriers are allowed to ask for bundles of distributed lanes. In short, the DTPP is the problem of matching demands and supplies over a transportation network.

This paper focuses on truck transportation, which is responsible for the majority of worldwide logistics businesses. For example, trucking represents 28.13% (the largest proportion) of the U.S. for-hire transportation services GDP in 2011 (NTS, 2012). Traditionally, the purchase of trucking service is achieved using a *request for proposal* and long-term contracts (Sheffi, 2004; Song and Regan, 2005). According to EEA (2010), the average weight utilization of trucks in Europe is under 60%. Similarly, the average operational costs of trucking in the U.S. are expected to rise significantly in recent years as compared to 2009, due mostly to a continuous increase in fuel prices and driver wages (ATRI, 2012). To reduce empty mileage and improve market efficiency, many companies have begun experimenting with alternative purchasing channels such as the third-party logistics e-marketplaces (e.g., www.leanlogistics.com, www.besttransport.com, and www.nte.com). For example, some firms with large private fleets, like Wal-Mart, buy transportation services for their unexpected demands via logistics e-marketplaces (Caplice, 2007). By exploiting the massive spare capacities, this new business model provides a win–win opportunity for shippers and carriers.

With the rise of Internet commerce, online auctions have been increasingly viewed as favorable tools for transportation procurement. As Lucking-Reiley (2000) pointed out, online auctions result in lower participation, information, and transaction costs, as well as the ability for asynchronous bidding, increased geographic and temporal conveniences, and easier access to wider markets. In the literature, there are three main auction mechanisms for the TPP: (i) *combinatorial auctions*, in which carriers are allowed to bid on groups of lanes (e.g., Sheffi, 2004; Chen et al., 2009; Ma et al., 2010; Kuo and Miller-Hooks, 2012; Remli and Rekik, 2013); (ii) *sequential auctions*, in which transportation demands arrive randomly over time and each demand is auctioned sequentially (e.g., Figliozzi et al., 2007; Garrido, 2007; Ağrali et al., 2008); and (iii) *double auctions*, in which bilateral bidding is allowed and the transportation market is cleared by the third-party auctioneer (e.g., Huang and Xu, 2013; Xu and Huang, 2013). In this paper, we are interested in combinatorial auctions. It is known that combinatorial auctions could capture the benefits of *complementarity*, in which the cost of serving a bundle of lanes is less than the sum of its individual costs (Song and Regan, 2005). For example, if one load should be hauled from A to B and another load should be hauled from B to A, then these two loads are complementary since grouping them together as an *atomic* bid induces zero empty mileage (if necessary constraints are satisfied). On the other hand, the "economies of scope" achieved in combinatorial auctions allow carriers to bid more aggressively, thereby incurring lower transportation costs for the shipper.

To date, there has been relatively little attention devoted to *allocatively efficient*, *incentive compatible* combinatorial auctions for the DTPP. Note that: (i) allocative efficiency implies that the allocation solution maximizes the sum of participants' values (social welfare) and (ii) incentive compatibility implies that truthful bidding reaches a Bayesian-Nash equilibrium (Krishna, 2009). It is clear that most of the combinatorial auctions cannot ensure allocative efficiency if incentive compatibility is sacrificed. Put another way, bidders' false valuations are likely to result in welfare loss, which would be significant when the maximal social welfare is small. To our best knowledge, Huang and Xu (2013) are among the first attempt to use one-sided VCG (Vickrey, 1961; Clarke, 1971; Groves, 1973) combinatorial auctions for the TPP. It is well known that VCG auctions lead to both incentive compatibility and allocative efficiency. However, in their study, transportation supply is assumed to be common knowledge and each carrier can only bid on one bundle of items.

This paper is devoted to filling this gap by considering the DTPP where carriers are allowed to bid on bundles of items. In particular, this paper aims to answer the following questions: (1) What are the efficient auction mechanisms for the DTPP? (2) What are the optimal bidding strategies for carriers? (3) How to make the implementation of auction simple and transparent to carriers (i.e., simplicity and practicability)? (4) How can our model be extended to incorporate other real-world operational factors (e.g., incomplete bids, and privacy preservation)?

We first construct a one-sided VCG (O-VCG) auction for the DTPP. The O-VCG auction realizes both incentive compatibility and allocative efficiency. This result implies that it is dominant for each carrier to submit his real costs for bundles, regardless of the opponents' bidding strategies. Hence, the problem of computing bids reduces to the problem of estimating costs for bundles. Given the cost structure, carriers' problem is only to identify feasible bundles that subject to routing and scheduling constraints and other operational constraints. Despite of truthful bidding and allocative efficiency, a general VCG auction is rarely conducted in real commerce (Rothkopf, 2007). One reason is that bidders may be reluctant to reveal their entire private information in the VCG auction (Rothkopf, 2007). Another reason seems to be that the VCG auction is too complicated for practitioners to understand (Ausubel, 2004). To facilitate the execution of auction, we next propose a primal–dual Vickrey (PDV) auction based on insights from the known *Ausubel auctions* (Ausubel, 2004, 2006) and the primal–dual algorithm. The PDV auction is actually a multi-round descending auction, which seems simple enough to be understood by any bidder.

Moreover, the PDV auction realizes VCG payments and truthful bidding under the condition of *seller-submodularity*, which implies that the effect of each individual carrier is decreasing when the coalition increases. Such is the case for the DTPP in an oversupplied transportation market. The winner determination problem of O-VCG auction is solved by the proposed