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Truthful multi-unit multi-attribute double auctions for perishable supply chain trading

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ABSTRACT

This paper aims to propose multi-attribute double auctions for perishable supply chain trading (PSCT). We first construct a multi-unit/single-unit multi-attribute double auction (MS-MDA) for PSCT where suppliers can submit bids on a single unit of one item (i.e., *single output restriction*). We then relax the single output restriction and propose a multi-unit multi-attribute double auction (M-MDA) for PSCT in which each supplier offers multiple units of one item. Both the MS-MDA and M-MDA mechanisms are incentive compatible, individually rational, budget balanced and computationally efficient. The computational study shows that all proposed mechanisms are of high allocation efficiency and practically implementable.

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1. Introduction

A perishable supply chain is characterized as a set of business entities (i.e. suppliers, manufacturers, distributors, and retailers) working together in production and delivery of perishable products (Mentzer et al., 2001). It covers the flow of perishable products from the source of supply to the point of consumption. Perishable products have been broadly defined as products which may have finite shelf-life, undergo noticeable physical status worsening, and experience remarkable value decrease in the view of customers over time (Amorim et al., 2013). Some examples include fruit, vegetables, meat, flowers, perfumes, alcohol, gasoline, photographic films, airline tickets, hotel bookings, fashion apparel, and electronics products. Perishable products involve not only consumer goods but also industrial products, military ordnance and blood, and take up a large proportion of products and services worldwide (e.g., Karaesmen et al., 2011; Firoozi et al., 2013). For instance, the global production volume of vegetables and melons was about 1135.69 million metric tons in 2013 (Statista, 2015). The performance of perishable supply chains has a significant impact on both the standard of living and the economic development.

Perishable supply chain trading (PSCT) is the process of buying, selling, transferring, or exchanging products, services, and information across a perishable supply chain. It can be regarded as a special type of supply chain trading. They share similarities. One is that both of them perform functions that match supply and demand, facilitate transactions and provide an institutional infrastructure (Bakos, 1998; Turban et al., 2009). Another similarity is that both of them generally involve suppliers, buyers and a market intermediary (Lee and Clark, 1996; Sashi and O'Leary, 2002). On the other hand, PSCT and supply chain trading differ in terms of two ways. Besides the price, quality, quantity, time and location of the products, PSCT considers the features of perishable products, such as high fluctuations in supply and demand, long lead time and a short shelf life (Pasternack, 1985; Cachon, 2003). Such features, however, are usually not incorporated in supply chain trading. Also,

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PSCT is responsible for reducing not only transaction costs but also transaction time, which is the time incurred in exchanging perishable products (Kambil and Van Heck, 1998). In contrast, supply chain trading adopts trading mechanisms for lowering transaction costs only.

To date, there have been two main auction mechanisms for PSCT: (i) *forward auctions*, in which buyers bid for perishable products that they are interested in, and the market intermediary sell these products on behalf of suppliers based on the received bids (e.g., Kambil and Van Heck, 1998; Kitahara and Ogawa, 2006; Crawford and Kuo, 2003; Sapio, 2008; Wang and Wang, 2011); and (ii) *double auctions*, in which both suppliers and buyers submit their bids, and the market intermediary determines resource allocation and prices on the basis of their bids (e.g., Kambil and Van Heck, 1995; Viswanadham et al., 2012; Miyashita, 2014). Many forward auctions have been used for PSCT, such as Dutch auction (Kambil and Van Heck, 1998; Crawford and Kuo, 2003; Kitahara and Ogawa, 2006), English auction, and descending/ascending auction (Sapio, 2008). The research and application of double auctions for PSCT are limited.

From a practical point of view, auctions can not only eliminate the problems of haggling but also achieve efficient allocation (e.g., Milgrom and Roberts, 1990; Chen et al., 2005). In addition, the bargaining costs and time involved in setting the price of perishable products can be reduced (e.g., Kambil and Van Heck, 1998). It is known that perishable products are rather diverse and heterogeneous. A single item can vary a lot by specifying different values for its attributes. One typical example is the rose. In Dutch flower auction, the length of the roses varies from 50 cm to over 90 cm (Van den Berg et al., 2001). The color of the roses may be red, brown, green, yellow, orange, purple, white, salmon, and so on. Due to the multi-attribute property of perishable products, a lot of efforts should be devoted to establishing exchange relationships between multiple suppliers and buyers.

Typically, four principles of auction mechanism design are recognized: *allocative efficiency* (AE) – the allocation maximizes the social welfare; *incentive compatibility* (IC) – truthful bidding forms a Bayesian-Nash equilibrium; (*ex-post*) *individual rationality* (IR) – all agents have non-negative utility to participate; and (*ex-post weak*) *budget balance* (BB) – the trade does not run at a loss (Krishna, 2009). As proved by Myerson and Satterthwaite (1983), no bilateral exchange can be AE, IR and BB simultaneously.

Multi-attribute auctions allow suppliers and buyers to compete over both price and nonmonetary attributes. Although (one-sided) reverse multi-attribute auctions have been extensively investigated (Teich et al., 2004; Pham et al., 2015), the research dealing with multi-attribute double auctions is limited. Also, most of the existing multi-attribute auctions are not truthful/IC.

To our best knowledge, this paper is among the first developing truthful, multi-unit multi-attribute double auctions. We consider the following PSCT problem. Three types of agents are involved, namely, multiple suppliers, multiple buyers and a market intermediary. The auction is initiated by the market intermediary (i.e., the central auctioneer). Then, suppliers submit bids to offer multiple units (or a single unit) of one item, and buyers bid to purchase multiple units of the same item. When the bidding process is over, the market intermediary determines the transactions between suppliers and buyers through the prescribed auction mechanism based on the set of bids accumulated over time. At last, perishable products are transported from the suppliers' locations to the buyers' locations directly according to the transactions. It is assumed that the market intermediary is in charge of collecting payments from buyers and paying the suppliers. Clearly, the auctions not only enable multiple suppliers to trade with multiple buyers, but also enjoy liquidity and efficiency advantages (Comerton-Forde and Rydge, 2006).

In particular, this paper will address the following questions: (1) How can a mechanism explicitly take into consideration more attributes than just price? (2) How to realize a truthful double auction when considering multiple attributes? (3) How to make the proposed double auction mechanisms practically implementable (e.g., BB, IR, and computational efficiency)?

The non-price attributes are modeled as constraints for matching suppliers with buyers. These constraints are divided into two groups: *hard constraints* and *soft constraints*. Soft constraints consist of *benefit soft constraints*, *cost soft constraints* and *interval soft constraints*. We also define the condition whether a supplier is qualified to match a buyer. Moreover, a simple multi-unit/single-unit multi-attribute double auction (MS-MDA) is proposed for PSCT with the *single output restriction*, in which each supplier only has a single unit of one item. The enhanced linear programming-based buyer competition approach (Chu and Shen, 2008) is adopted to clear the market. We then devise a multi-unit multi-attribute double auction (M-MDA) if the single output restriction is relaxed. Both the MS-MDA and M-MDA mechanisms ensure IC, IR, BB and high allocative efficiency. Finally, the trading prices are determined based on the linear relaxation formulations, so as to achieve computationally efficient implementation.

The reminder of this paper is organized as follows. In Section 2, we review the literature related to auction-based PSCT, multi-attribute auctions and truthful double auction mechanisms. Section 3 introduces the auction model. Section 4 and Section 5 present the MS-MDA and M-MDA respectively regarding to the model, mechanism and properties. To evaluate the efficiencies of the MS-MDA and M-MDA mechanisms, a computational analysis is conducted in Section 6. Section 7 summarizes the contributions and suggests some directions for future research.

2. Literature review

In the literature, three streams of research are related to this study: (1) auction-based PSCT; (2) multi-attribute auction; and (3) truthful double auction mechanisms. Many auction mechanisms have been utilized in practice for PSCT, such as, traditional Dutch auction (Kambil and van Heck, 1998), Dutch auction with "Mari" stages (Kitahara and Ogawa, 2006), dual Dutch auction (Crawford and Kuo, 2003), English auction, as well as descending/ascending auction (Sapio, 2008). In Dutch

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