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Schemes to reward winners in combinatorial double auctions based on optimization of surplus

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ABSTRACT

Although the combinatorial double auction model has been proposed for buyers and sellers to trade goods conveniently for over a decade, it is still not widely adopted. Several factors that hinder the adoption of combinatorial double auction model include the high complexity to determine winning bids and the lack of studies on the schemes to benefit winners in an auction. A relevant challenging research issue is to study how to make this business model acceptable in the real world. Motivated by the deficiency of existing studies on these factors, we will study how to take advantage of the surplus of combinatorial double auctions to benefit the winners based on surplus optimization and schemes to reward winners. The contributions of this study are threefold: (1) we propose a computationally efficient approximate algorithm to tackle the complexity issue in combinatorial double auctions, (2) we propose schemes to reward winners based on the surplus of auctions and (3) our study paves the way for the promotion of combinatorial double auction model. Our main results include (i) a surplus optimization problem formulation that takes transaction cost and supply/demand constraints into account (ii) a divide-and-conquer approach to decomposing the optimization problem into subproblems and a subgradient method to determine shadow price (iii) several schemes to reward winners and (iv) numerical results that indicate that the winners can be better off by applying our schemes.

1. Introduction

One of the recent trends in the development of auction mechanisms is combinatorial auctions. In a combinatorial auction, bidders can place bids on a combination of goods according to personal preferences rather than just individual items. Combinatorial auctions are beneficial if complementarities exist between the items to be auctioned. Well-known combinatorial auction examples are the auction of Federal Communications Commission's radio spectrum licenses, the sale of airport time slots, and allocation of delivery routes. Combinatorial auctions have been extensively studied, e.g. Sandholm (2000), Abrache et al. (2004), Perugini et al. (2005), Catalán et al. (2009), Leskelä et al. (2007), Meeus et al. (2009), Özer and Özturan (2009), Yang et al. (2009) and Harsha et al. (2010). An excellent survey on combinatorial auctions can be found in (de Vries and Vohra, 2003) and (Pekeč and Rothkopf, 2003). In the past years, combinatorial double auctions attracted researchers' attention. A combinatorial double auction combines the mechanism of double auction with combinatorial auction to make buyers and sellers trade goods conveniently. Combinatorial double auctions, which allow buyers and sellers to submit bids, are much more efficient than several one-sided auctions combined. There are also studies on double auctions or combinatorial double auctions, e.g. Fan et al. (1999), Ba et al. (2001), Choi et al. (2008) and Schellhorn (2009). Doubled auction and combinatorial double auction mechanisms have been applied in a few problem domains, including resource allocations in grids (Li et al., 2009a; Li et al., 2009b) and the electricity market (Block et al., 2008; Nicolaisen et al., 2001; Wang and Yin, 2004).

Although the combinatorial double auction model makes it possible for buyers and sellers to trade goods conveniently, it poses several challenging research issues.The problem to determine winners in combinatorial auctions or combinatorial double auctions is called the winner determination problem (WDP). In the existing literature, one of the most challenging research topics on combinatorial auctions and combinatorial double auctions is the complexity to solve WDP. The WDP of combinatorial auctions and combinatorial double auctions is difficult to solve from a computational point of view (Rothkopf et al., 1998; Xia et al., 2005) due to exponential growth of the number of combinations. The WDP of combinatorial auctions can be modelled as a set packing problem (SPP) (Sandholm, 1999; Sandholm, 2000; Sandholm, 2002; Andersson

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et al., 2000; Fujishima et al., 1999; Hoos and Boutilier, 2000; Vemuganti, 1998; Xia et al., 2005). To describe the computational complexity of a decision problem, the notion of 'nondeterministic algorithm' is defined by computer scientists. A nondeterministic algorithm is an algorithm consisting of two stages: guessing and checking (or verification). A nondeterministic algorithm at first guesses a solution and then checks the validity of this solution. If the checking (or verification) stage of a nondeterministic algorithm is of polynomial time complexity, this nondeterministic algorithm is called a nondeterministic polynomial algorithm. A decision problem that can be solved by a nondeterministic polynomial algorithm is called a nondeterministic polynomial (NP) problem. The class NP refers to decisions problems that can be solved by nondeterministic polynomial algorithms. A decision problem D is said to be NP-complete if (i) D belongs to the class NP and (ii) every problem in NP is polynomially reducible to D. A problem D satisfying condition (ii) is said to be NP-hard, whether or not it satisfies condition (i). Sandholm showed that determining the winners so as to maximize revenue in a combinatorial auction is NP-complete (Sandholm, 1999; Sandholm, 2000; Sandholm, 2002).

The WDP of combinatorial double auctions are also notoriously difficult to solve from the computation point of view. Several restricted classes of combinatorial double auctions have been studied. Fan et al. (1999) considered divisible goods in combinatorial double auctions and formulated the WDP as a linear programming problem which is not computationally challenging. Ba et al. (2001) proposed a combinatorial double auction mechanism for non-divisible public goods and proved that such combinatorial double auction can be solved in polynomial time under weak assumptions. However, the approach of Ba et al. (2001) is limited to combinatorial double auctions with public goods only. In the existing literature, Xia, Stallaert and Whinston considered non-divisible goods in a combinatorial double auction which maximizes the difference between buyers' total payment and sellers' total revenue (Xia et al., 2005). They showed that a general combinatorial double auction can be reduced to a combinatorial single-sided auction which is a multi-dimensional knapsack problem, a problem known to be a NP-hard in computational complexity.

To cope with the complexity of WDP, many algorithms have been developed for combinatorial auction problems. Exact algorithms have been developed for the SPP problem, including iterative deepening A* search (Sandholm, 2000) and direct application of available CPLEX Integer Programming solver (Andersson et al., 2000). Gonen and Lehmann proposed branch and bound heuristics for finding optimal solutions for multi-unit combinatorial auctions (Gonen and Lehmann, 2000). Jones and Koehler studied combinatorial auctions using rule-based bids (Jones and Koehler, 2002). Sandholm (1999) and Fujishima et al. (1999) considered a class of single-sided combinatorial auction model with a unique seller of unique items and bundles with distinct goods and unique items and developed specialized algorithms for it. Xia et al. (2005) showed that the use of branch-and-bound and LP relaxations at each node performed better than the specialized algorithms for the WDPs of combinatorial auctions described in Sandholm (1999) and Fujishima et al. (1999). However, there are few studies on development of computationally efficient algorithms for combinatorial double auctions.

The WDP of combinatorial double auctions can be modeled as an integer programming problems. The Lagrangian relaxation approach provides a computationally efficient approach to integer programming problems (Fisher, 2004). In the existing literature, several studies on application of Lagrangian relaxation approach to WDP of combinatorial auctions or combinatorial reverse auctions are available. For example, Andersson et al. (2000) proposed a Lagrangian heuristic for combinatorial auction problems. Application of Lagrangian relaxation approach to solve WDP of combinatorial reverse auctions has also been studied in (Hsieh, 2010) and (Hsieh and Lin, 2012a; Hsieh and Lin, 2012b). However, there is a lack of study on application of Lagrangian relaxation approach to solve WDP of combinatorial double auctions. As mentioned by Xia et al. (2005), the subgradient optimization approach may be a promising approach to the WDP of combinatorial double auctions. There are few studies (with the exception of Hsieh and Liao, 2012) on the development of computationally efficient algorithms for solving the WDP of combinatorial double auctions with non-divisible goods based on subgradient optimization approach. This motivates us to investigate the effectiveness of combining the Lagrangian relaxation technique with subgradient optimization approach for combinatorial double auctions.

In addition to computational complexity, there are other factors that hinder the adoption of combinatorial double auctions in the real world. One of the factors is the lack of an effective method to attract more bidders and allocate the value generated in combinatorial double auctions. A mediator that provides combinatorial double auction service must attract as many bidders as possible, including potential buyers and sellers, to place bids. If few bids are placed in a combinatorial double auction, it may turn out that no solution can be found. It calls for the development of an effective method to attract more bidders to place bids to generate a feasible solution for a combinatorial double auction. Once the winners of a combinatorial double auction have been determined, a multi-party contract will be established among the winners and the mediator. How to divide the value of the generated solution among the winners and the mediator is also critical for realizing the benefits of combinatorial double auctions. The above discussions motivate us to study an effective way to attract bidders based on proper allocation of the value generated in a combinatorial double auction.

One effective way to attract more potential buyers and sellers to place bids is to guarantee that all the winning buyers will acquire their required items at a price lower than or equal to their original bid price and all the winning sellers will sell their available items at a price higher than or equal to their original bid price. To see how one may make this way work, note that the mediator usually charges transaction fee to the winners of an auction in practice. For the mediator, the surplus of a combinatorial double auction consists of the transaction fee paid by the winners and the difference between the overall price of buyers' winning bids and the overall price of sellers' winning bids. If the surplus is positive, there is plenty of room for the mediator to reward the surplus of a combinatorial double auction to the winners. How to take advantage of the surplus to reward the winners is an important issue. In this paper, we will study how to reward the winners based on optimization of surplus in combinatorial double auctions that consider transaction cost and supply/demand constraints. The goal of this paper is to propose an algorithm for finding a solution for optimization of surplus in combinatorial double auctions and develop several schemes to reward surplus based on the solution.

In this paper, we consider a class of combinatorial double auction problems in which there are a set of buyers, a set of potential sellers and a mediator for trading non-dividable goods. Each buyer and seller places bids based on the required items to be purchased and the available items to be sold, respectively. We assume all the participants tell truth. Several constraints must be satisfied in determination of winners. These include the supply/demand constraints, the constraints on the sellers' available items and the non-negative surplus constraint. Our methodology to reward the surplus to the winners includes two stages: (1) optimization of surplus and (2) allocation of surplus. We will propose an efficient algorithm for finding approximate solutions at the surplus optimization stage and develop several schemes that can be tailored or modified by the mediator as needed to reward surplus to the winners at the surplus allocation stage.