Decision Support Systems 51 (2011) 480–492

Contents lists available at ScienceDirect

Decision Support Systems

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

A public procurement combinatorial auction mechanism with quality assignment

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ARTICLE INFO

Article history:
Received 9 July 2010
Received in revised form 1 December 2010
Accepted 6 February 2011
Available online 10 February 2011

Keywords:
Combinatorial auctions
Economic analysis
Government procurement
Mechanism design
Quality assignment
Social welfare

ABSTRACT

This article focuses on mechanism design for *quality assignment combinatorial procurement auctions*. We model how the participants can maximize *social surplus*, the difference between gross utility and total cost in electronic procurement, while selecting appropriate quality standards for the procured items. In typical forward combinatorial auctions, the goal is to maximize the sum of all buyers' valuations. In our setting, however, to achieve high buyer utility with low supplier cost, the selected quality levels for the procured items from the suppliers must exceed some predetermined minimum threshold. So the identification of capable suppliers and the corresponding quality assignments are crucial, since buyer utility and supplier cost will be affected by the buyer's quality choice. We develop a novel mechanism to balance the interests of buyers and sellers. Our proposed *quality assignment Vickrey–Groves–Clarke* (QA-VCG) *mechanism* is incentive-compatible, provides constraints on partial participation, and is efficient in quasi-linear preferences. In consideration of the perspective of the buyer as a government auctioneer, we also propose a revised mechanism to implement the goal of achieving minimal procurement costs, and appropriate benefits for participating suppliers. We provide a numerical illustration of our QA-VCG mechanism, and an extension that addresses an iterative combinatorial auction mechanism design in our context.

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1. Introduction

Electronic combinatorial auctions have been applied in a variety of environments involving economic transactions. They have the potential to play an important role in electronic transactions for supply chain management procurement [33] and other contexts [45,46]. For example, Logistics.com (www.logistics.com) in the transportation and shipping industry has conducted industry-specific B2B procurement combinatorial auctions, and Net Exchange (www.nex.com) has procured transportation services for Sears Logistics [50]. Home Depot regularly uses combinatorial auctions to procure trucking services [27]. Lee et al. [51] also have reported on an algorithm for optimal combinatorial auction bidding in truck route selection in support of such applications. IBM, which has significant ongoing research at its R&D centers around the world [12–16,57,58], also has been doing procurement through combinatorial auctions on behalf of Mars Incorporated and many other organizations [34].

In many other application settings though, the buyer in an electronic combinatorial auction for supply procurement is not a business enterprise. Municipal, county, provincial, state and central governments, and other public sector organizations are likely to benefit as well [30,46]. Combinatorial auctions can be used to procure services and project help, as well as goods, reflecting the needs of public procurement. We focus on the reverse auction version of combinatorial auctions for public procurement, where the emphasis is on social welfare. Our purpose especially matches the requirements for government auctions that can be held via the Internet in China, where state and private enterprises are involved in procurement, and where this research originated. Recently, for example, Catalan et al. [19] have studied the practical application of Internet-based combinatorial procurement auctions in the context of the procurement activities for food supplies by the Government of Chile, which provides more than 1.8 million meals daily to public school children at an annual cost of US$360 million.

Combinatorial auctions have several features that affect the efficacy of their design: their *computational feasibility* [55], their *efficiency for winner determination* [18], and the *economic efficiency* of their mechanism [37,45].[1] The computational efficiency of winner determination

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[1] Some special issues and problems occur in the context of combinatorial auctions [43]. These include the *exposure problem* and *bidding expressiveness* [56], the *threshold problem* and the *moving efficiency problem* [8], and the *ties problem* in iterative combinatorial auctions [59]. These issues have all been studied extensively. The interested reader should see the following surveys, which provide useful interpretive information on the definitions of the problems, the extent to which they diminish the value of combinatorial auction mechanisms, and the variety of approaches that have been suggested to permit their resolution [25,28,38,42,44–46,60,73]. Spulber [67] is especially helpful to bridge the economics and IS literature related to market microstructure and the role of electronic market intermediaries.

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doi:10.1016/j.dss.2011.02.012

algorithms has been explored in many research articles to date on combinatorial auctions [5,17,63]. Combinatorial auctions are challenging mechanisms to implement effectively. It is hard to solve for exact solutions when the number of suppliers is relatively large [65], and when there are information asymmetries between the buyer and suppliers [11]. In addition, there are often problems with free riding [24] on the part of bidders.

From the perspective of economics and management science, the central issues that exist in the optimal design of combinatorial auctions are allocation efficiency and revenue maximization (or cost minimization) [37]. *Allocation efficiency* occurs when both the total value for the winners and the buyer's valuation are maximized, and is a primary goal in auctions involving a government auctioneer, such as the United States Federal Communications Commission for broadcast spectrum and transmission rights in radio networks [53]. Another application area is the procurement auctions of airport commissions for landing and takeoff slots at regional airports [40].

We view allocation efficiency in terms of *social surplus maximization* from the procurement, from the point of view of both the government and suppliers. *Revenue maximization* is also important from the perspective of a government, which typically wishes to minimize its total cost of procurement [6,7,60]. However, these goals may contradict each other in different economic settings. For example, this can occur when there is a reserve price that does not permit the auction allocation priority ranking to be in synch with the ordered values of the bids that are made [54]. Krishna and Perry [47] suggest that a tradeoff is probably necessary in most auction mechanism design cases. *Mechanism design* is intended to solve the problem of effective auction implementation [9]. It views the marketplace as having self-interested rational agents with private information who act as participating suppliers in an auction. Their private information characterizes the suppliers' cost structure and auction bidder's demeanor. Some typical supplier type descriptors include supplier preferences, the schedule of supplier values for different quantities and qualities, the time in the auction (e.g., early or late or both) when the supplier makes a bid, and so on.

The purpose of this paper is to design a mechanism for combinatorial reverse auction-based procurement to achieve maximum social welfare, which has the utilitarian social goal of optimizing total surplus for both the auctioneer and the winning supply bidders. We emphasize that the role of the auctioneer that we wish to model in this work is a government or public entity procurement agent. For clarity related to the procurement in supply chain management, we will refer to bidders as *suppliers* throughout. The specific characteristics of combinatorial auctions that we will treat in the procurement context involve *heterogeneous goods* and different *quality standards*. The property of heterogeneous goods is the same property that we see in normal combinatorial auctions [20]. However, the second property — quality standards assignment — is somewhat unique in procurement auctions.

The remainder of this article is organized as follows. Section 2 discusses the background literature and theory on the Vickrey–Clarke–Groves (VCG) mechanism for combinatorial auctions, as a departure point for the remainder of the article. Section 3 presents our proposed variant, a VCG mechanism for combinatorial auctions with the possibility of quality choices to be made by the auction bidders, and with suppliers who have the flexibility to provide different bundles of procurement goods with differing degrees of quality. Section 4 discusses incentive compatibility, and presents our first analytical results to show that the social choice function in our quality *assignment VCG mechanism* (QA-VCG) can be truthfully-implemented based on identifiable dominant strategies. Section 5 deepens our analysis of the QA-VCG mechanism, by analyzing individual rationality and permitting bidders to decide whether they wish to participate in the auction. Next is Section 6, which discusses the QA-VCG mechanism's performance from the point of view of the auction operator. In Section 7, we present a numerical illustration of the operation of the QA-VCG mechanism. Section 8 extends the results of our QA-VCG mechanism to the case of multi-round auctions, where truth-telling round-by-round is no longer an essential goal. Section 9 concludes with contributions and limitations that can be addressed in future research.

2. The Vickrey–Clark–Groves mechanism

Discussions about the application of the *Vickrey–Clark–Groves* (VCG) *mechanism* [21,31,71,72] in normal combinatorial auctions can be found in the works of Ausubel [1–3], Ausubel and Milgrom [4,5], Bikhchandani and Ostroy [17], Parkes [57], Rothkopf et al. [64], and elsewhere. Sun and Yang [68,69] focused on combinatorial auctions for substitute goods or complementary goods to achieve allocation efficiency, by a new Walrasian tâtonnement process called a *double-track procedure*. The VCG mechanism family provides a useful basis for our efforts to design a mechanism for combinatorial procurement auctions that addresses the key issues in social welfare maximization from a public procurement perspective.

The VCG mechanism family has several well-known virtues. The first is that it creates incentives for truthful reporting as the dominant strategy of any bidder. In addition, its outcomes are always efficient. Another virtue is its scope of application: the fundamental rules of VCG can adapted to suit other settings based on the addition of some extra constraints. Finally, the *revenue equivalence theorem* tells us that the auctioneer's revenue under the VCG mechanism will not be less than that from any other efficient mechanism. Despite these attractive properties, however, the VCG mechanism has not often been applied in real-world settings. The main reasons relate to weaknesses in the VCG mechanism that include: the winner determination problem, bid preparation and communication costs, the failure of truthful reporting with budget constraints, the information revelation problem, the auction's vulnerability to shill bids, and decreased revenues or cost savings in the presence of a larger number of bidders [23,48,62].

Hidvégi et al. [32] introduced a *binary Vickrey auction* (BVA) mechanism to address the problem of computational complexity related to the winner determination problem. Their mechanism allocates goods in bundles based on sequentially-decreasing power-of-two items over multiple rounds. Their mechanism is able to handle auctions for specific bidding quantities of multiple identical items. In public procurement auctions, the above concerns may not be controlling though. For example, as auctioneers governments tend to pay the most attention to social welfare and allocation efficiency, rather than revenues. Shilling, or pseudonym use, and non-monotonic revenues for the auctioneer are not critical issues in government procurement. When procurement costs are going to be large, government procurement specialists will scrutinize the identities of all potential suppliers, and prequalify them for bidding. Also, they can make it a criminal act for a supplier to use a pseudonym — and enforce that prohibition. Further, knowing that the participation of additional potential supplier enhances the probability of achieving higher social welfare, the non-monotonicity of the government's revenue in terms of the number of suppliers will not be critical either.

To handle the quality-related combinatorial assignment, we will extend the classical VCG mechanism by incorporating suppliers' cost functions, and by capturing the quality assignment nature of procurement combinatorial auctions in an analytical model. This is our *quality assignment Vickrey–Clark–Groves* (*QA-VCG*) *mechanism*. In the QA-VCG mechanism, the supplier's cost function can be used to characterize the auction bids, and the level of willingness-to-pay or valuation for providing supplies in a given combinatorial auction that involves not-for-profit operations. We will show the basis for allocation efficiency, the incentive compatibility that makes dominant equilibrium strategies possible, and the individual rationality of the suppliers that obtains in their use of the mechanism. We also show

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