Strategy/False-name Proof Protocols for Combinatorial Multi-Attribute Procurement Auction: Handling Arbitrary Utility of the Buyer

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1. INTRODUCTION

This paper develops new protocols for a combinatorial, multi-attribute procurement auction in which each sales item (task) is defined by several attributes called quality, the buyer is the auctioneer (e.g., a government), and the sellers are the bidders. Furthermore, multiple tasks exist, and both buyer and sellers can have arbitrary (e.g., complementary/substitutable) preferences on a bundle of tasks.

Traditionally, very little theoretical work has been conducted on multi-attribute auctions, with the notable exception of [1]. In this work, bidders can bid on both price and quality, and bids are evaluated by a scoring rule designed by the buyer. In addition, first score and second score sealed bid auctions have been proposed. However, in this work, the quality is assumed to be one-dimensional and assigning multiple tasks is not considered.

In our previous work, we presented a model of combinatorial, multi-attribute procurement auctions and developed a VCG-based protocol and a false-name-proof protocols [2]. However, they can only be applied when the buyer's gross utility has an additive form. More specifically, there is a chance that these protocols cannot satisfy Individual Rationality (IR) in general, i.e., the buyer's net utility can be negative. In this paper, we show that if a surplus function is concave, then the VCG protocol satisfies IR and the protocol is also false-name-proof.

Furthermore, we present a modification of the VCG protocol that satisfies IR, even if the concavity condition is not satisfied. This protocol's key idea is to introduce a special type of bidder called the reference bidder. We assume that the auctioneer knows the upper-bound of the reference bidder's cost. Introducing such a reference bidder is similar to setting reservation prices in standard combinatorial auctions. Also, we develop a new false-name-proof protocol based on the idea of the Leveled Division Set (LDS) protocol [3].

2. MODEL

First, we define the model used in this paper.

- There exists a single buyer 0.
- There exists a set of sellers/bidders $N = \{1, 2, \ldots, n\}$.
- There exists a set of tasks $T = \{t_1, \ldots, t_m\}$.
- Each bidder i privately observes his type θ_i.
- For each task t_j, quality $q_j \in Q$ is defined.
- A possible allocation of tasks to bidders is represented as $\overrightarrow{B} = (B_1, \ldots, B_n)$, where $B_i \subseteq T$ and for $i \neq k$, $B_i \cap B_k = \emptyset$ holds.
- A profile of qualities is represented as $\overrightarrow{q} = (q_1, \ldots, q_m)$.
- For a quality profile $\overrightarrow{q}$ and bundle $B_i = \{t_{i,1}, t_{i,2}, \ldots\}$, we represent a projection of B_i onto $\overrightarrow{q}$ as $\overrightarrow{q}_{B_i} = (q_{t_{i,1}}, q_{t_{i,2}}, \ldots)$.
- The cost of bidder i when B_i is allocated and the achieved quality profile $\overrightarrow{q}_{B_i}$ is represented as $c(\theta_i, B_i, \overrightarrow{q}_{B_i})$. We assume c is normalized as $c(\theta_i, \emptyset, ()) = 0$.
- The gross utility of buyer 0, when the obtained quality profile is $\overrightarrow{q}$, is represented as $V(\overrightarrow{q})$.
- The payment from the buyer to each seller/bidder i is represented as p_i.
- We assume that each participant's utility is quasi-linear, i.e., for each seller i, his utility is represented as $p_i - c(\theta_i, B_i, \overrightarrow{q}_{B_i})$. Also, for the buyer, her (net) utility is $V(\overrightarrow{q}) - \sum_{i \in N} p_i$.

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- For an unallocated task t_j, we assume that the quality of t_j is $0 \in Q$. V is normalized by $V(\overrightarrow{q}_0) = 0$ as $\overrightarrow{q}_0 = (0, 0, \ldots, 0)$.

Note that although there is only one parameter q_j for representing the quality of task t_j, this does not mean that our model can handle only one-dimensional quality, i.e., q_j can be a vector of multiple attributes.

3. VCG-TYPE PROTOCOL

One serious limitation of the VCG protocol is that it cannot guarantee IR for the buyer. Actually, in [2] we have proved that, for both the buyer and the sellers, no protocol simultaneously satisfies all of the following conditions: Pareto efficiency, strategy-proofness, and IR.

3.1 Sufficient Condition where VCG is IR and False-name-proof

For a set of bidders X, social surplus function $U(X)$ is defined as follows.

$$U(X) = \max_{(\overrightarrow{B}, \overrightarrow{q})} V(\overrightarrow{q}) - \sum_{j \in X} c(\theta_j, B_j, \overrightarrow{q}_{B_j}),$$

where $\overrightarrow{B}$ is chosen so that $\forall j \notin X, B_j = \emptyset$.

DEFINITION 1. *We say $U(\cdot)$ is concave over bidders if for all possible sets of bidders X, Y, Z, where $X \subset Y$, the following condition holds: $U(X \cup Z) - U(X) \geq U(Y \cup Z) - U(Y)$.*

The intuitive meaning of this condition is that the increase in the social surplus by adding Z becomes smaller if the original set becomes larger. The following theorem holds.

THEOREM 1. *If $U(\cdot)$ is concave, then the VCG protocol satisfies IR for the buyer.*

3.2 Modified VCG Protocol

Next, we show a modification of the VCG protocol that satisfies the buyer's IR without the concavity condition. First, we introduce a notion called *reference bidder* r, which has the following properties.

- We assume the buyer knows the upper-bound of costs when task t_k is allocated to the reference bidder at quality q_k, i.e., the buyer knows c_{r,t_k,q_k}, where $c_{r,t_k,q_k} \geq c(\theta_r, \{t_k\}, (q_k))$ holds.
- The cost of the reference bidder is additive, i.e., for arbitrary B, $\overrightarrow{q}_B = (q_1, q_2, \ldots, q_k, \ldots)$, $c(\theta_r, B, \overrightarrow{q}_B) = \sum_{t_k \in B} c(\theta_r, \{t_k\}, (q_k))$ holds. Therefore $c(\theta_r, B, \overrightarrow{q}_B) \leq \sum_{t_k \in B} c_{r,t_k,q_k}$ holds.
- For arbitrary quality profile $\overrightarrow{q} = (q_1, \ldots, q_k, \ldots)$, $V(\overrightarrow{q}) \geq \sum_{t_k \in M} c_{r,t_k,q_k}$ holds. This means that for any quality, the buyer's net utility is non-negative when all tasks are allocated to the reference bidder and the payment is equal to the sum of the upper-bounds.

It is quite natural to assume that a bidder has some knowledge about the upper-bounds of costs for some other bidders. For example, assume a company is making a decision on whether to create a product in-house or to outsource the production, i.e., the company can make some profit by in-house production but the cost might be reduced by outsourcing. The company can make this decision by performing an auction. In this case, the company itself (when it does in-house production) can be considered the reference bidder.

Furthermore, a manufacturer can publish listed prices for some products. The government can use an auction to discover better deals than the listed prices by soliciting other manufacturers. In such a case, the manufacturer that publishes the listed prices can be considered as the reference bidder.

We applied the following modification to the VCG.

- The optimal allocation and the quality profile that maximize the social surplus are calculated in the same way as for the VCG, except that for the reference bidder r, c_{r,t_k,q_k} is used instead of his true cost.
- If the quality profile is $q^* = (q_1^*, \ldots, q_k^*, \ldots)$ and a set of tasks B_r is allocated to the reference bidder, the payment to the reference bidder is equal to $\sum_{t_k \in B_r} c_{r,t_k,q_k^*}$

The following theorem holds.

THEOREM 2. *The modified VCG protocol is IR for both the buyer and sellers.*

4. FALSE-NAME-PROOF PROTOCOL

The VCG protocol is not false-name-proof even if we introduce the reference bidder. By modifying the Leveled Division Set (LDS) protocol [3], which was developed for standard combinatorial auctions, we obtain a new false-name-proof, combinatorial multi-attribute procurement auction protocol. We omit the LDS protocol details due to space constraints. The following theorems hold.

THEOREM 3. *The LDS protocol satisfies IR for both the buyer and sellers.*

THEOREM 4. *The LDS protocol is false-name-proof.*

5. FUTURE WORKS

Although there are many situations where the existence of a reference bidder is quite reasonable, the assumption that the buyer's utility is non-negative for all possible quality profiles if the reference bidder performs all tasks might be too restrictive. We plan to develop protocols that work under weaker assumptions. Also, we intend to experimentally evaluate the efficiencies of our protocols.

6. REFERENCES

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