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Electronic service matching: Failure of incentive compatibility in Vickrey auctions

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ABSTRACT

We consider pricing schemes for matching customers and providers on double-sided markets for electronic services. While existing second-best solutions are incentive compatible, the associated payment functions are difficult to implement in real-world settings. Based on the Vickrey–Clarke–Groves (VCG) and the k-pricing mechanism, we propose two straightforward payment schemes that offer a practical alternative to the second-best solution. Our experiments provide evidence that the VCG payments fail to implement incentive compatibility. This failure is due to the interdependency of the participants' utilities.

1. Introduction

Matching the right pairs of competitive customers and providers for electronic services on double-sided markets is an important optimization problem in Operations Research [2]. On these markets, multiple service providers offer electronic services of a specified quality of service (QoS), while multiple customers demand these services at a specific QoS. To this end, matching markets have recently emerged in different business areas including Cloud computing [1].

In common market settings, strategic participants may engage in bid manipulation in order to influence their transaction prices. While first-best solutions are not available in such settings [10], second-best mechanisms for matching customers and providers with interdependent utilities have been proposed [15]. Although such mechanisms satisfy incentive compatibility and individual rationality, the associated payment schemes are difficult to implement in real-world scenarios. Attempts to simplify the payment scheme, however, may open the way for strategic participants to increase their utilities by misrepresenting their bids. Thus, before modifying the payments, the mechanism designer must obtain an accurate estimation for the potential utility gain that participants can achieve due to strategic bid manipulation.

Prior research studies the average utility gain of participants with independent utilities on markets for electronic services. The mechanism proposed by Schnizler et al. uses k-pricing to provide a simple payment scheme that is well-suited for real-world electronic service exchange [12]. Although their approach allows for estimating the utility gain of strategic participants, it does not consider interdependent utilities. Lee analyzes the manipulability of stable matching mechanisms to quantify the utility gain participants can expect through bid manipulation [8]. Yet concrete payment schemes for real-world markets are missing. In the context of generalized assignment problems, Fadaei and Bichler propose truthful approximation mechanisms in payment-free environments [3]. Fadaei and Bichler use the optimal welfare value as a benchmark to estimate the efficiency loss due to strategic bidding. Because they consider mechanism design without money, no payment rules are provided. Widmer and Leukel [15] provide a lower bound for the efficiency of a second-best mechanism that allocates electronic services with private quality information. Although they specify the incentive compatible payments of customers and providers in double-sided markets, these payment rules turn out to be inexpedient for implementing the associated mechanism in real-world environments.

The objective of our research is to study the efficiency loss of a mechanism with two straightforward payment schemes for electronic service matching in double-sided markets. We apply these two payment schemes to markets where participants have interdependent utilities. The first payment scheme is based on the prominent Vickrey–Clarke–Groves (VCG) pricing rules [14], which satisfy incentive compatibility in single-unit and certain multi-unit procurement auctions [5]. The second payment scheme is based on k-pricing introduced by Sattherthwaite and Williams [11], where the price is simply calculated as the arithmetic mean of

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customer valuation and provider cost. Mechanisms with k-pricing, however, are not incentive compatible [10]. In a set of simulation experiments, we study the potential utility gains that participants can expect through strategic bid manipulation.

We find that in our model with interdependent utilities, the prominent VCG mechanism is not incentive compatible. The reason for the failure of incentive compatibility is that strategic customers and providers can manipulate their perceived impact on social surplus through the utilities of their matched partners. Hence, participants are able to increase their utilities by manipulation even when VCG pricing is used. The results of our experimental evaluation for both payment schemes provide an accurate estimation for these utility gains.

2. Formal framework

There are two disjoint sets of participants in the market, namely customers and providers. In order to obtain benchmark results for arbitrary market settings, we begin by assuming an equal number N of customers and providers on each market side in this article. This assumption is consistent with prior research investigating mechanisms for allocating electronic services [12]. We revisit this assumption in our discussion of future research directions (cf. Section 4.3).

Each provider attempts to sell an electronic service to one customer, and each customer seeks to buy a service from one provider. Each customer i demands for a privately known QoS θ_i, and each provider offers their service at a privately known QoS σ_j.

If customer i receives the service of provider j, i produces the pairwise private valuation $v(\theta_i, \sigma_j)$. This valuation depends on i's desired quality, as well as on the difference between its own desired quality and provider j's actual quality. This situation depicts a market in which customer valuation functions are non-monotonic in the quality offered by the provider. For instance, a customer may prefer a service with medium over high computational capacity. A high-capacity service is well able to process many simultaneous requests from the customer's application that uses this service. If, however, this application does not have enough computational power or resources, the application will fail to answer these simultaneous requests in due time. This failure leads to higher buffering in the application and thus longer response times. Therefore, a customer's valuation must take into account the application that uses the service and the tradeoff between being idle or buffering heavily [6]. Therefore, we assume that any mismatch in desired quality and actual quality creates adjustment problems for the customer. That is, $v(\theta_i, \sigma_j)$ is maximized when the supplied quality and the desired quality are equal (i.e., when $\theta_i = \sigma_j$). By assumption, the maximal value is increasing in θ_i.

On the supply side, if provider j sells a service to customer i, j accrues a service provision cost $c(\sigma_j, \theta_i)$, which depends on the actual quality and on the difference between the own actual quality and the customer's desired quality. If a provider produces a quality lower than the quality desired by a customer, this provider incurs higher cost from not fulfilling the requirements. If, in contrast, a provider maintains higher quality than desired, their cost increases due to idle resources [4]. Hence, we assume that $c(\sigma_j, \theta_i)$ is minimized when $\sigma_j = \theta_i$ and that the minimal value is increasing in σ_j. This assumption captures the fact that a mismatch in actual quality and desired quality creates higher provision cost resulting from after-sales customer service cost and missed opportunity cost. Both $v(\theta_i, \sigma_j)$ and $c(\sigma_j, \theta_i)$ are assumed to be thrice differentiable.

Customers and providers use quasi-linear utilities. Hence, customer i paying t_c for receiving an electronic service from j obtains a payoff of

$$u_c(\theta_i, \sigma_j) = v(\theta_i, \sigma_j) - t_c, \tag{1}$$

and provider j receiving t_p for delivering the service to customer i obtains a payoff of

$$u_p(\sigma_j, \theta_i) = t_p - c(\sigma_j, \theta_i). \tag{2}$$

This research takes the perspective of a social planner, who is interested in maximizing the sum of the participants' welfare. Therefore, the social planner aims at maximizing the social surplus among all participants. Let $x_{ij} \in \{0, 1\}$ denote the decision variable, which is 1 if customer i receives the electronic service from provider j in the final allocation, and 0 otherwise. Thus, the mechanism faces the following optimization problem:

$$\max_{x_{ij}} \sum_{i=1}^{N} \sum_{j=1}^{N} (v(\theta_i, \sigma_j) - c(\sigma_j, \theta_i)) x_{ij} \tag{3}$$

$$\text{s.t.} \quad 0 \leq \sum_j x_{ij} \leq 1 \quad \forall i \tag{4}$$

$$0 \leq \sum_i x_{ij} \leq 1 \quad \forall j. \tag{5}$$

The expression in (3) adds up the pairwise match surplus across all customers and providers and determines the allocation that maximizes the social welfare. Notice that the payments t_c and t_p do not appear in (3) because they add up to zero due to the budget balance constraint. Constraints (4) and (5) ensure that each customer is matched to exactly one service provider in the final allocation.

3. Mechanism definition

3.1. Allocation rule

The allocation rule of the mechanism must ensure that the final allocation of customers and providers maximizes the social welfare defined in (3). In many auction settings, it is difficult to determine the winners of the auction due to computational complexity issues. In supermodular environments, however, it turns out that the allocation rule, which maximizes the social welfare, adopts a rather simple form. Let $\rho_\theta(\theta_i) = |\{\theta_k \in \theta : \theta_k \geq \theta_i\}|$ be the rank of desired quality θ_i within the vector of all customers' desired qualities $\theta = \{\theta_1, \ldots, \theta_N\}$. Define $\rho_\sigma(\sigma_i)$ similarly for providers. Then, the allocation rule is given by

$$x_{ij} = \begin{cases} 1 & \text{if } \rho_\theta(\theta_i) = \rho_\sigma(\sigma_j) = k \ \wedge \ v(\theta_i, \sigma_j) - c(\sigma_j, \theta_i) \geq 0, \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

In other words, the mechanism accepts the bids θ_i of all customers and the bids σ_j of all providers, sorts each side in descending order, and allocates customers and providers that are on the same rank from top to bottom. That is, the allocation rule of the mechanism is positively assortative. It maximizes the optimization problem in (3) because the pairwise surplus $v(\theta_i, \sigma_j) - c(\sigma_j, \theta_i)$ is a supermodular function. If the pairwise surplus function is supermodular, the optimal match function is positively assortative [13].

3.2. Pricing

After having obtained the welfare maximizing allocation rule in (6), it is crucial to determine the payments made by the participants for electronic service allocation. For designing an efficient mechanism, these payments must guarantee that no participant has an incentive to deviate from their true bid. That is, the payments must ensure incentive compatibility. It is well-known that a pricing scheme based on the VCG mechanism [14] is incentive compatible for a single customer who buys one unit of a product from a set of providers [5]. Moreover, the VCG mechanism ensures incentive compatibility in settings with many customers